PreFix

Annual Progress Report

Sept 2022 – Sept 2023

Electricity Distribution

nationalgrid

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Contents

1. Executive Summary

Project Pre-Fix is funded through Ofgem's Network Innovation Allowance (NIA) funding mechanism and has a budget of £1.64M. It was registered in autumn 2021 and will be complete by March 2024.

We are conducting this project with the intention of being able to improve our customer's experience of power cuts. We think that the Pre-Fix project can achieve this by enabling faster restoration and potentially intercepting defects before they occur. Innovation funding is being spent as this project seeks to overcome the barriers to wide-spread High Voltage (HV) pre-fault capability represented by developing alternatives to a vendor tie in model that is associated with proprietary software. Overcoming vendor tie in will mean that National Grid Electricity Distribution (NGED) can interoperate pre-fault sensitive devices. This interoperability will translate into a lower unit cost to deliver this capability.

This project has utilised HV pre-fault capture capable devices to demonstrate how they can contribute into a common data platform. This project has demonstrated how existing network devices, such as power quality monitors and protection relays might also help contribute to HV pre-fault detection in addition to their typical function. The project has also shown how consistent operational dashboards and reports can be developed from this platform to enable a consistent policy driven approach to be implemented across an organisation. Key activities that have been carried out during the project include:

- Use of trial data from other DNO's to inform platform design and support testing
- Architecture specification for the Common Distribution Information Platform (C-DIP)
- Interoperability specification and setting of pre-fault gathering devices
- Design of common operational user interfaces.
- Live trial of devices, platform and reports

This project is a partnership between NGED and Nortech Management Ltd.

This report details progress of the project, focusing on the last twelve months from September 2022 to September 2023.

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https://www.nationalgrid.co.uk/innovation/projects/pre-fix

1.1. Project Background

We are conducting this project to build a capability that will enable us to react more efficiently to faults that have occurred or defects that are about to occur. To enable this, we will need to be able to share information with operational staff about these defects; but to obtain this information, we will need to be able to gather and process information from devices on the network. Building a DNO platform rather than relying on vendor platforms means that we are able to ensure that different devices can all inter-operate and drive consistent operational policy.

Over a 2 and half year project duration, Pre-Fix is planned to deliver a pre-fault and disturbance information platform. The extent of the platform is depicted in Figure 1.

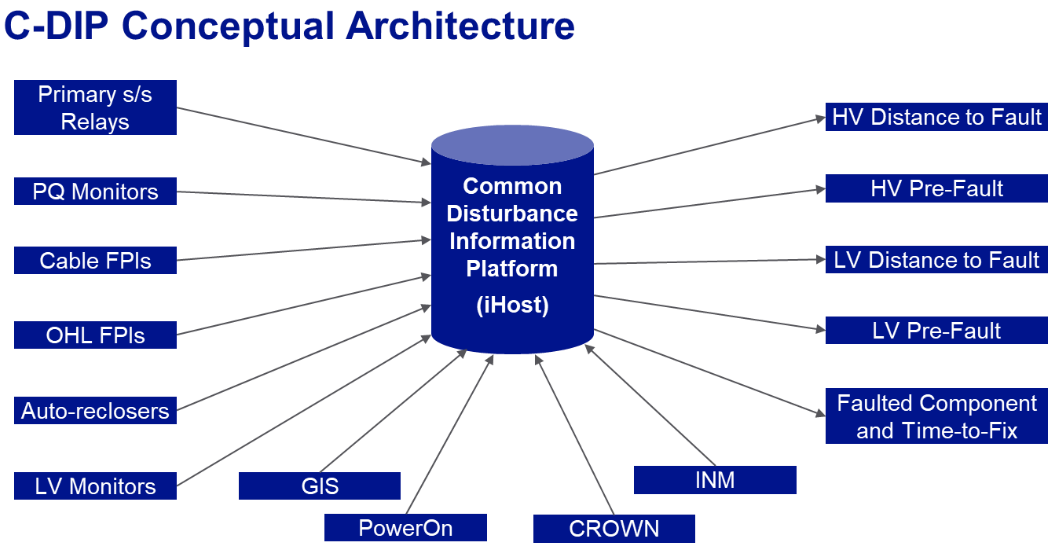

C-DIP Conceptual Architecture

Figure 1 Overview of Common Disturbance information Platform

Whilst significant developments and advances have taken place at LV for fault detection and location, at present NGED does not have a business ready distance-to-fault or distance-to-pre-fault solution for HV networks.

Any solutions that do exist in the current marketplace are tied into specific vendors (hardware and software platforms) and their distribution management systems (DMSs). It is not financially or practically viable for NGED to make use of such systems without embarking on a potential replacement programme for PowerOn itself.

Even if a platform were available, as it is vendor-specific, it would not allow data from multiple devices at multiple locations to be brought together to extract information in a coordinated and corroborative way. Therefore, the development of such a platform is required and, for game-changing performance in RIIO-ED2, the way to BaU adoption needs to be paved via development and demonstration.

The overall aim of the project is to develop a common disturbance information platform (C-DIP) that can gather disturbance information from various network devices (PQ monitors etc.). By running automated analysis on the data gathered from network devices and aligning it with network information, operationally useful information would be shared with field staff and fault restoration managers. This project seeks to establish whether devices already in NGEDs supply chain can deliver HV pre-fault data. Demonstration of this feature would help keep the unit cost of introducing a pre-fault capability lower than using bespoke pre-fault devices and potentially help increase the accuracy.

The 'DO NOTHING' approach will mean that reactive responses will continue to be the method by which NGED addresses faults within the distribution network. This is forecast to be costly (due to labour intensive methods for fault finding, investment in more cables and more automation) and, with fault occurrence more likely, will not sustain NGED's high level of customer service excellence. Moreover, lack of comprehensive data could lead to network condition uncertainties that could lead to costly and time-consuming reinforcement works that could have been better targeted at other parts of the network.

The Network Innovation Allowance (NIA) provides NGED with the mechanism to demonstrate the benefits of Pre-Fix in a low-risk way. If demonstrated and proven, the solution will provide a proactive and integrated way to manage network faults by enhancing visibility of fault characteristics and location. Pre-Fix will support NGED in operating its network in a more strategic way (for example, using proactive network switching and reconfiguration to avoid/reduce customer interruptions and load shedding if a fault was to occur). It will also facilitate the identification and locating of faults more promptly and with greater certainty.

More information can be found within our project registration document found here.

1.2. Project Progress

This is the third progress report. It covers progress from September 2022 to the end of September 2023. In the last 12 months the project has completed several project deliverables, including the following:

- The Common Disturbance Information Platform (C-DIP) has been built, tested and trialled in the field.
- Distance to fault and distance to pre-fault algorithms have been implemented within the C-DIP environment.
- Class I and Class II devices have been installed with live data successfully fed into the C-DIP.

- Third party device integration into C-DIP has been proven.
- An equipment settings philosophy document, to facilitate integration of further third party devices, has been developed.
- Training and dissemination to NGED staff on the use of the C-DIP platform has been provided.

The project has also progressed with the following work:

- Pre-fault location predictions.
- Post-fault analysis using distance to defect algorithms.
  Validating pre-fault localisation predictions using post fault locations.
- Disturbance waveform classification algorithms.
- Regular data and analysis meetings have taken place to discuss trial progress and learning points.

1.3. Procurement

The following table details the current status of procurement for this project.

Table 1 - Procurement Details

Provider	Services/Goods	Area of project applicable to	Anticipated Delivery Dates
Nortech	Devices for live trial	Capturing Pre-Fault data and proving data flows	Additional NX44's and PQM's delivered in July 2023
Nortech	Software Development	Development and trial of the C-DIP	Ongoing support and development

1.4. Project Risks

A proactive role in ensuring effective risk management for Pre-Fix is taken. This ensures that processes have been put in place to review whether risks still exist, whether new risks have arisen or whether the likelihood and impact of risks have changed. Reporting of significant changes that will affect risk priorities has also been undertaken to deliver assurance of the effectiveness of control.

Contained within Section 7 of this report are the current top risks associated with successfully delivering Pre-Fix as captured in our Risk Register. Section 7 provides an update on the most prominent risks identified at the project bid phase.

1.5. Project Learning and Dissemination

Project lessons learned and successes are captured throughout the project lifecycle. These are captured through a series of on-going reviews with stakeholders and project team members, and will be shared in lessons learned workshops at the end of the project. These are reported in section 5 of this report.

The project has also produced two papers for the CIRED 2023 conference and disseminated these at the event. The two papers can be found at the following links:

DELIVERING THE BENEFITS FROM A COMMON DISTURBANCE INFORMATION PLATFORM

APPLYING MACHINE LEARNING TO POWER QUALITY SIGNALS TO DETECT COMPONENT FAILURE SIGNATURES AND PREVENT UNPLANNED HV OUTAGES

In addition, the outputs of Pre-Fix were also presented at the CIGRE UK Conference on “The application of data analytics to enhance power system performance” (London), Friday 27th May 2023 and the Ofgem, UKRI and Carbon Trust Workshop on “Market Access and Commericalisation” (On-line Webinar), Tuesday 18th July 2023.

2. Project Manager's Report

2.1. Project Background

This project seeks to overcome the barriers to wide-spread High Voltage (HV) pre-fault capability represented by vendor tie in and proprietary software.

This project utilises HV pre-fault capture capable devices from different manufacturers to demonstrate how they can all contribute into a common data platform. This project also demonstrates how certain existing network devices such as power quality monitors, protection relays and Low Voltage (LV) monitors might also help contribute to HV pre-fault detection in addition to their basic functions. This project is also developing dashboards and reports that enable a consistent policy driven approach to be implemented across an organisation.

The objectives of this project are to:

- Develop and validate a process to enable pre-fault capable devices from different manufacturers to contribute information onto the same platform.
- Develop and validate processes to enable pre-fault information to be drawn out of this platform.
- Develop and validate standard reports that enable consistent and effective pre-fault policy driven decision making to be made in an operational environment.

The project will be deemed a success if the following criteria are achieved:

- Demonstration of how to gather and then utilise data from existing WPD specification equipment in the pre-fault data chain, including protection relays and power quality monitors.
- Demonstration of how pre-fault information from diverse devices can be gathered into a central location.
- An application guide for how, where and when to deploy different pre-fault equipment.
- A user interface to present pre-fault data in a manner that is useful, consistent and meaningful to operational users.
- A prototype operational protocol for how to leverage technical applications into operational outcomes.

2.2. Project Progress

The project is structured into to five Work Packages as summarised in Table 1. The trial specifications for Work Package 1 are competed and will be revisited at the end of the trial. The following sections provide updates on the other work packages.

Table 1: Work Package Summary

Work Package	Description
Work Package 1 Specification.	This Work Package records the requirements that must be delivered from all of the systems to be developed within this project
Work Package 2 Design and development.	This Work Package conducts the deeper design requirement to deliver WP1, including design documentation and operational protocols, which will explain: (i) Deployment and application guidelines; (ii) Design and setting Documentation (for permanent fit devices); and (iii) Communication philosophy and requirements.
Work Package 3 Build and Install.	This Work Package constructs the systems required to deliver the functionality, installs the trial infrastructure and tests ahead of trial.
Work Package 4 Testing.	This Work Package tests the components and system ahead of the trials
Work package 5 Trial.	This Work Package conducts a system trial to prove the system requirements in an operational context.

2.3. Work Package 2 - Design & Development

During the period from September 2022 to September 2023, progress was made in the following areas of Work Package 2 (Design and Development):

1. User Interface Wireframe Design (for Data Analytics)
2. Data Definitions and Data Dictionary Development
3. Distance to Fault and Classification Algorithm Development
4. Device Settings Philosophy Development

The design and development was split into three separate iterative sprints to continually improve the design of the C-DIP features. To date, two iterations have been completed with one in progress and due for completion by December 2023. In addition, a system design record has been maintained to capture any deviations from the original functional specifications.

Each area of Work Package 2 development is described in more detail in the subsections that follow.

2.3.1. User Interface Wireframe Design (for Data Analytics)

This delivered a wireframe design of a User Interface for trial purposes and data analytics purposes. Further details of the embodiment of the wireframe design are given in Section 2.4.

2.3.2. Data Definitions and Data Dictionary Development

This delivered the definitions and dictionary of data that was gathered into the C-DIP, used, processed and generated as an output by the platform. Further details of the embodiment of the data dictionary design are given in Section 2.4.

The data dictionary continues to be developed as the project continues to include the integration of third party devices and with pre-fault/post fault data analysis.

2.3.3. Distance to Fault and Classification Algorithm Development

This delivered the first-pass algorithm to create the provision and functionality for: (i) detecting disturbances; (ii) locating disturbances; and (iii) assessing time-to-fail metrics.

Further details of the embodiment of the distance-to-fault and classification algorithms are given in Section 2.4 with the learning captured in Section 5.2.

Subsequent algorithm updates and evolutions, following data gathering and learning, were delivered via software releases during the project life-cycle.

2.3.4. Device Settings Philosophy Development

This delivered setting documentation for capture devices. This recorded the settings for devices utilised within Pre-Fix trials as well as laying out the expectations for third-party vendors wishing to enhance the functionality of their equipment. This would allow further devices to be compatible with the philosophy of Pre-Fix and be ‘C-DIP-ready’. As part of Pre-Fix, the enhancement and adaption of equipment functionality was demonstrated by Powerside, the vendor of the PQube3 power quality monitoring equipment. In this case, the functionality of the PQube3 was enhanced to deliver electrical current distortion-based triggers (rather than overcurrent triggers or voltage distortion-based triggers). This meant the PQube3 was more readily able to discern and distinguish between nature load changes on the network and disturbances as a result of pre-fault network activity. Further details of the embodiment of the settings design philosophy are given in Section 2.4 with the learning captured in Section 5.1. A draft copy of the device settings philosophy document can be found on the Pre-Fix project website.

2.4. Work Package 3 - Build and Install & Work Package 4- Testing

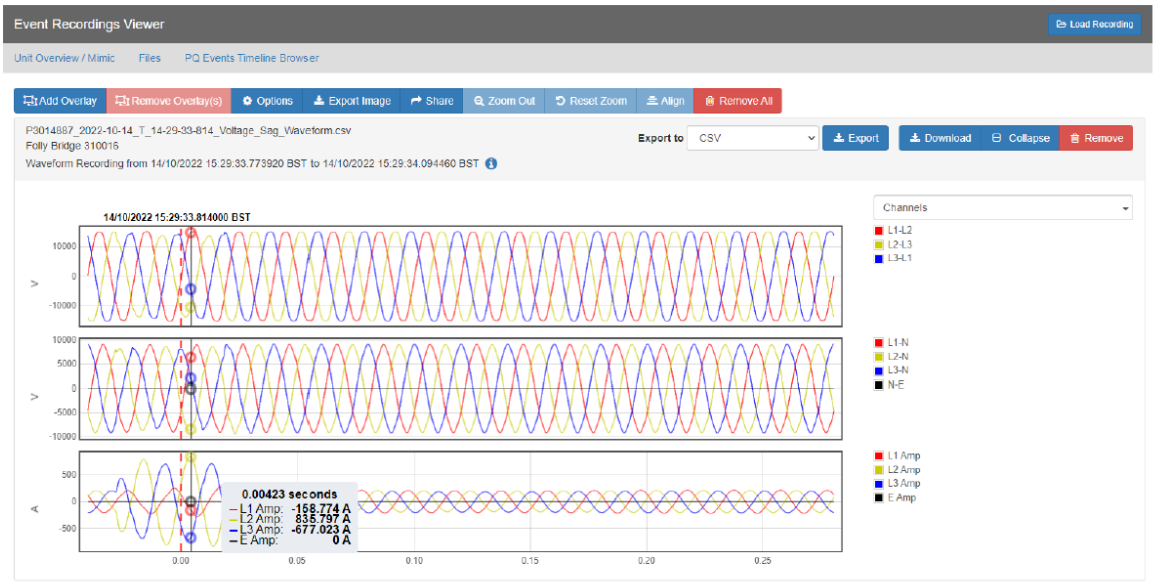
Progress in these WPs are summarised in the following sub-headings. The reporting from WP3 and WP4 has been merged to allow combined commentary on the development work and quality testing to fall in the same section.

2.4.1. C-DIP Development and Testing

During the period September 2022 to September 2023, the functionality of the Common Disturbance Information Platform (C-DIP) was developed, built, tested on the bench and trialled in the field. This section of the report spans across the various work packages to outline and illustrate the key features, outputs and user interfaces of the C-DIP.

2.4.1.1. Waveform Viewer

Functionality was developed with C-DIP to allow system users to view source waveforms generated by the various classes of devices. Furthermore, the suite of features within C-DIP enabled users to both manually and automatically merge and synchronise different waveform files (for example, where different devices capture the individual phase waveforms associated with the same disturbance event, or devices along an HV feeder all observe the same disturbance event and the user wishes to compare waveforms). Examples of the Waveform Viewer functionality are given in Figure 2 (Class I Device, PQube3 waveform viewer), Figure 3 (Class II Device, Smart Navigator 2.0 waveform viewer, including the automatic synchronisation and merging of waveforms) and Figure 4 (showing the manual synchronisation of waveforms).

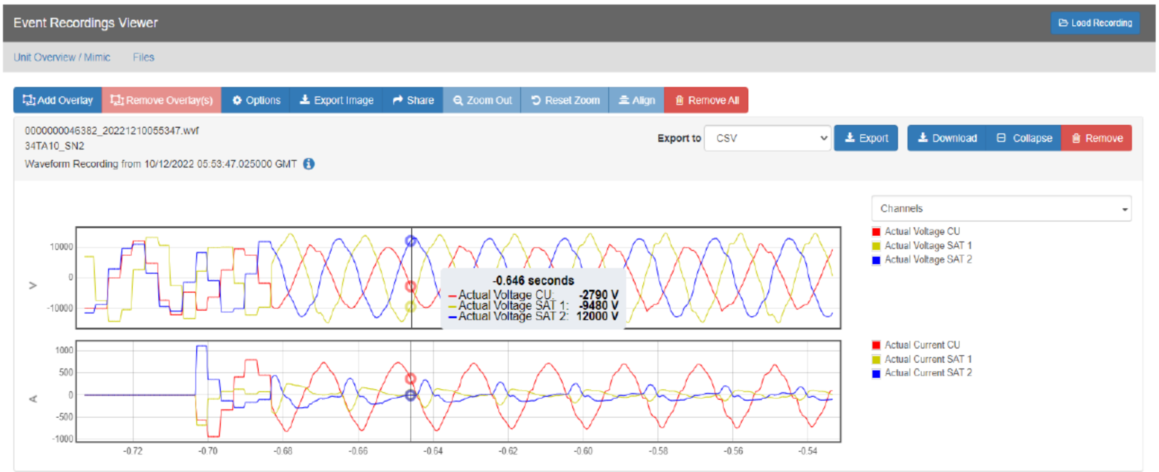


P3014887_2022-10-14_T_14-29-33-814_Voltage_Sag_Waveform.csv
Folly Bridge 310016
Waveform Recording from 14/10/2022 15:29:33.773920 BST to 14/10/2022 15:29:34.094460 BST

Export to: CSV

0.00423 seconds
L1 Amp: -158.774 A
L2 Amp: 835.797 A
L3 Amp: -677.023 A
E Amp: 0 A

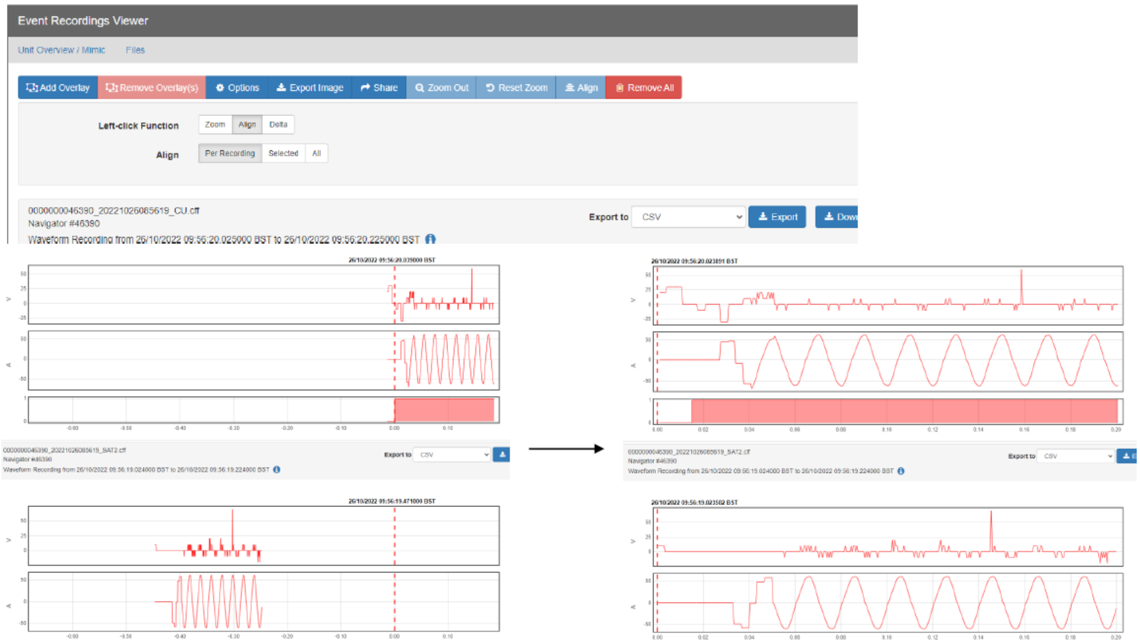
Figure 2 - Class I Device, PQube3 waveform viewer



0000000046382_20221210055347.wvf
34TA10_SN2
Waveform Recording from 10/12/2022 05:53:47.025000 GMT

-0.646 seconds
Actual Voltage CU: -2790 V
Actual Voltage SAT 1: -9480 V
Actual Voltage SAT 2: 12000 V

Figure 3 - Class II Device, Smart Navigator 2.0 waveform viewer, including the automatic synchronisation and merging of waveforms



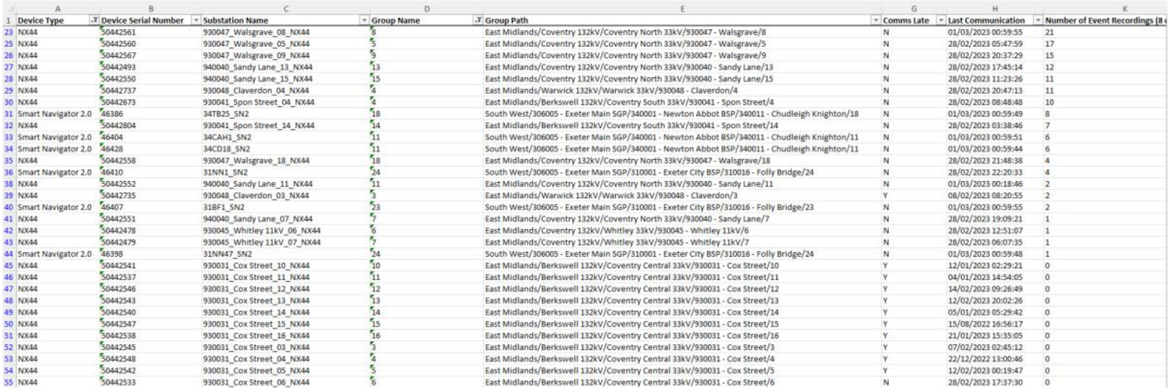
Left-click Function: Align
Align: Per Recording

0000000046390_20221026085619_CU.cff
Navigator #46390
Waveform Recording from 26/10/2022 09:56:20.025000 BST to 26/10/2022 09:56:20.225000 BST

Figure 4 - Manual synchronisation of waveforms

2.4.1.2. Device Activity Report

The C-DIP allows user-defined reports to be generated. One such report – the Device Activity Report – proved to be a very powerful tool for gaining insight into the level of pre-fault and post-fault activity across the HV feeders within the trial networks. An illustration of the Device Activity Report output is given in Figure 5. For each class of device that saw activity within a user-defined period, the report returned the type of device, its serial number, network location, communications health status and the number of events (binaries and waveforms) recorded. This dataset could then be used as the basis for further analysis to determine the criticality of HV feeders (for example, ranking them by total number of events recorded during a given period).



	A	B	C	D	E	G	H	K
1	Device Type	Device Serial Number	Substation Name	Group Name	Group Path	Comms Late	Last Communication	Number of Event Recordings (8
23	NX44	50442561	930047_Walsgrave_08_NX44	8	East Midlands/Coventry 132kV/Coventry North 33kV/930047 - Walsgrave/8	N	01/03/2023 00:59:55	21
25	NX44	50442560	930047_Walsgrave_05_NX44	5	East Midlands/Coventry 132kV/Coventry North 33kV/930047 - Walsgrave/5	N	28/02/2023 05:47:59	17
26	NX44	50442567	930047_Walsgrave_09_NX44	9	East Midlands/Coventry 132kV/Coventry North 33kV/930047 - Walsgrave/9	N	28/02/2023 20:37:29	15
27	NX44	50442493	940040_Sandy Lane_13_NX44	13	East Midlands/Coventry 132kV/Coventry North 33kV/930040 - Sandy Lane/13	N	28/02/2023 17:45:14	12
28	NX44	50442550	940040_Sandy Lane_15_NX44	15	East Midlands/Coventry 132kV/Coventry North 33kV/930040 - Sandy Lane/15	N	28/02/2023 11:23:26	11
29	NX44	50442737	930048_Claverdon_04_NX44	4	East Midlands/Warwick 132kV/Warwick 33kV/930048 - Claverdon/4	N	28/02/2023 20:47:13	11
30	NX44	50442673	930041_Spon Street_04_NX44	4	East Midlands/Berkswell 132kV/Coventry South 33kV/930041 - Spon Street/4	N	28/02/2023 08:48:48	10
31	Smart Navigator 2.0	46386	34TB25_SN2	18	South West/306005 - Exeter Main SGP/340001 - Newton Abbot BSP/340011 - Chudleigh Knighton/18	N	01/03/2023 00:59:49	8
32	NX44	50442804	930041_Spon Street_14_NX44	14	East Midlands/Berkswell 132kV/Coventry South 33kV/930041 - Spon Street/14	N	28/02/2023 03:38:46	7
33	Smart Navigator 2.0	46404	34CAH1_SN2	11	South West/306005 - Exeter Main SGP/340001 - Newton Abbot BSP/340011 - Chudleigh Knighton/11	N	01/03/2023 00:59:51	6
34	Smart Navigator 2.0	46428	34CD18_SN2	11	South West/306005 - Exeter Main SGP/340001 - Newton Abbot BSP/340011 - Chudleigh Knighton/11	N	01/03/2023 00:59:44	6
35	NX44	50442558	930047_Walsgrave_18_NX44	18	East Midlands/Coventry 132kV/Coventry North 33kV/930047 - Walsgrave/18	N	28/02/2023 21:48:38	4
36	Smart Navigator 2.0	46410	31NN1_SN2	24	South West/306005 - Exeter Main SGP/310001 - Exeter City BSP/310016 - Folly Bridge/24	N	28/02/2023 22:20:33	4
38	NX44	50442552	940040_Sandy Lane_11_NX44	11	East Midlands/Coventry 132kV/Coventry North 33kV/930040 - Sandy Lane/11	N	01/03/2023 00:18:46	2
39	NX44	50442735	930048_Claverdon_03_NX44	3	East Midlands/Warwick 132kV/Warwick 33kV/930048 - Claverdon/3	Y	08/02/2023 08:20:55	2
40	Smart Navigator 2.0	46407	31BF1_SN2	23	South West/306005 - Exeter Main SGP/310001 - Exeter City BSP/310016 - Folly Bridge/23	N	01/03/2023 00:59:55	2
41	NX44	50442551	940040_Sandy Lane_07_NX44	7	East Midlands/Coventry 132kV/Coventry North 33kV/930040 - Sandy Lane/7	N	28/02/2023 19:09:21	1
42	NX44	50442478	930045_Whitley 11kV_06_NX44	6	East Midlands/Coventry 132kV/Whitley 33kV/930045 - Whitley 11kV/6	N	28/02/2023 12:51:07	1
43	NX44	50442479	930045_Whitley 11kV_07_NX44	7	East Midlands/Coventry 132kV/Whitley 33kV/930045 - Whitley 11kV/7	N	28/02/2023 06:07:35	1
44	Smart Navigator 2.0	46398	31NN47_SN2	24	South West/306005 - Exeter Main SGP/310001 - Exeter City BSP/310016 - Folly Bridge/24	N	01/03/2023 00:59:48	1
45	NX44	50442541	930031_Cox Street_10_NX44	10	East Midlands/Berkswell 132kV/Coventry Central 33kV/930031 - Cox Street/10	Y	12/01/2023 02:29:21	0
46	NX44	50442537	930031_Cox Street_11_NX44	11	East Midlands/Berkswell 132kV/Coventry Central 33kV/930031 - Cox Street/11	Y	04/01/2023 14:54:05	0
47	NX44	50442546	930031_Cox Street_12_NX44	12	East Midlands/Berkswell 132kV/Coventry Central 33kV/930031 - Cox Street/12	Y	14/02/2023 09:26:49	0
48	NX44	50442543	930031_Cox Street_13_NX44	13	East Midlands/Berkswell 132kV/Coventry Central 33kV/930031 - Cox Street/13	Y	12/02/2023 20:02:26	0
49	NX44	50442540	930031_Cox Street_14_NX44	14	East Midlands/Berkswell 132kV/Coventry Central 33kV/930031 - Cox Street/14	Y	05/01/2023 05:29:42	0
50	NX44	50442547	930031_Cox Street_15_NX44	15	East Midlands/Berkswell 132kV/Coventry Central 33kV/930031 - Cox Street/15	Y	15/08/2022 16:56:17	0
51	NX44	50442538	930031_Cox Street_16_NX44	16	East Midlands/Berkswell 132kV/Coventry Central 33kV/930031 - Cox Street/16	Y	21/01/2023 15:35:05	0
52	NX44	50442545	930031_Cox Street_03_NX44	3	East Midlands/Berkswell 132kV/Coventry Central 33kV/930031 - Cox Street/3	Y	07/02/2023 02:45:12	0
53	NX44	50442548	930031_Cox Street_04_NX44	4	East Midlands/Berkswell 132kV/Coventry Central 33kV/930031 - Cox Street/4	Y	22/12/2022 13:00:46	0
54	NX44	50442542	930031_Cox Street_05_NX44	5	East Midlands/Berkswell 132kV/Coventry Central 33kV/930031 - Cox Street/5	Y	12/02/2023 00:19:47	0
55	NX44	50442533	930031_Cox Street_06_NX44	6	East Midlands/Berkswell 132kV/Coventry Central 33kV/930031 - Cox Street/6	N	28/02/2023 17:37:30	0

Figure 5 – Illustrative Device Activity Report output

2.4.1.3. Single Line Diagrams

The Single Line Diagram (SLD) feature within C-DIP embedded fundamental building blocks for the operational use of the system by ingesting NGED's HV models (in SINCAL source format). This allows users to interact with the SLDs to mark-up locations as a planning tool for the escalation fit of equipment. The SLD data (combined with topological and coordinate data) also acted as the fundamental building block allowing users view geographical plots of potential defect locations, automatically generated post-fault fault flow (based on FPI alarms and distance-to-fault estimations) and automatically generated distance-to-fault network location estimations. The SINCAL model ingestion and conversion process is shown in Figure 6. The Single Line Diagram viewer feature is shown in Figure 7 and the Single Line Diagram interactive editor is shown in Figure 8.

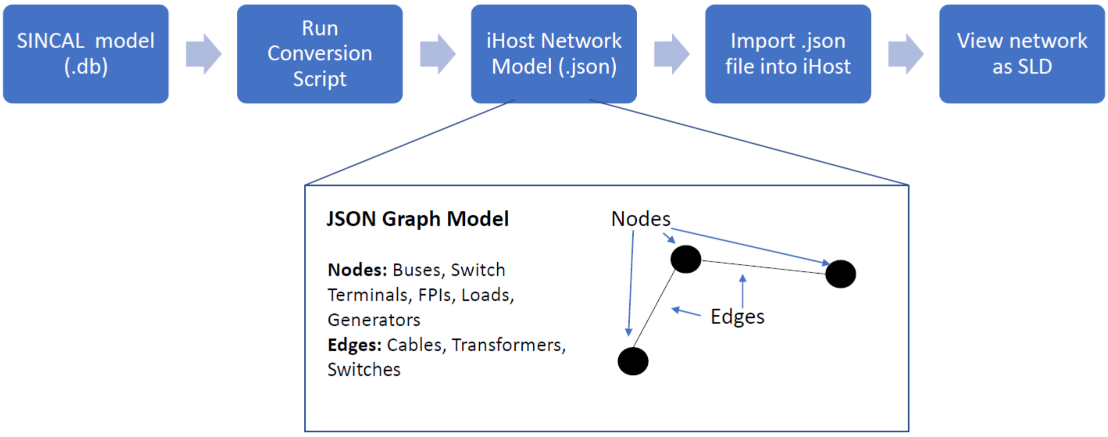
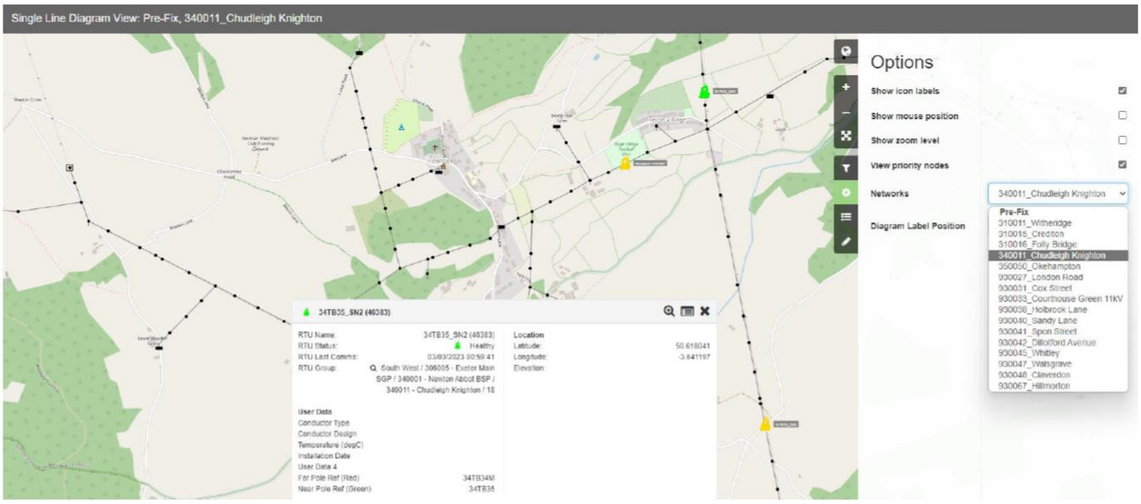


Figure 6 - SINCAL model ingestion and conversion



Single Line Diagram View: Pre-Fix, 340011_Chudleigh Knighton

Options

Show icon labels ☑

Show mouse position ☐

Show zoom level ☐

View priority nodes ☑

Networks: 340011_Chudleigh Knighton

Diagram Label Position

34TB35_SN2 (46383)

RTU Name: 34TB35_SN2 (46383)

RTU Status: Healthy

RTU Last Comms: 03/03/2023 00:59:41

RTU Group: South West / 306005 - Exeter Main SGP / 340001 - Newton Abbot BSP / 340011 - Chudleigh Knighton / 18

Location

Latitude: 50.618041

Longitude: -3.641197

Elevation:

User Data

Conductor Type

Conductor Design

Temperature (degC)

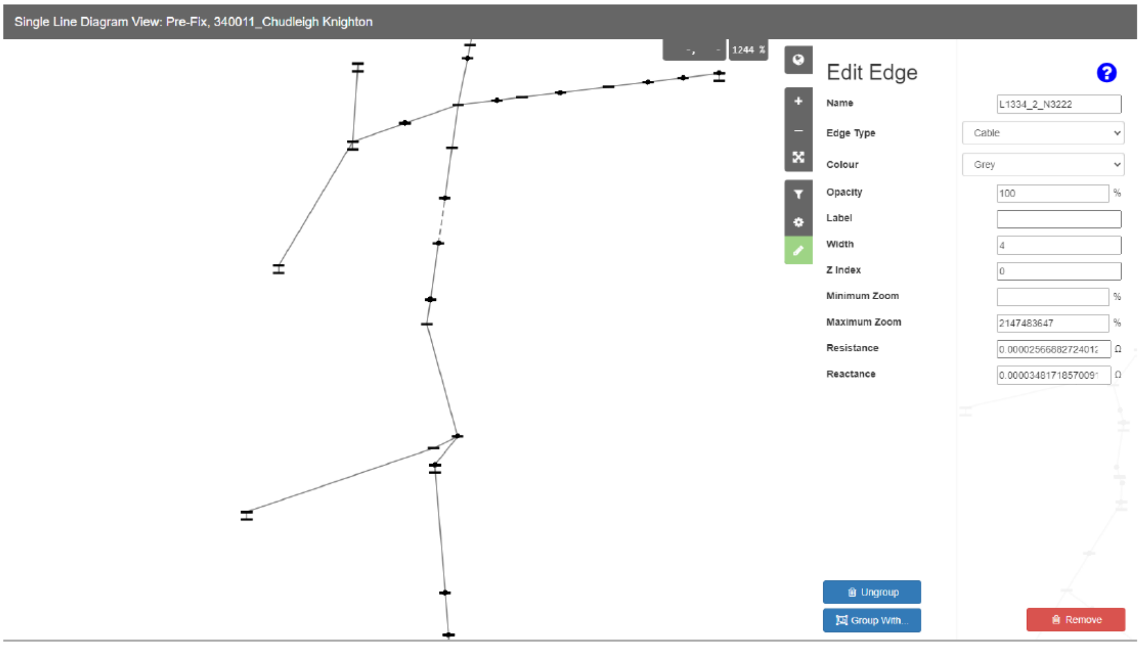
Installation Date

User Data 4

Far Pole Ref (Red): 34TB34M

Near Pole Ref (Green): 34TB35

Figure 7 - Single Line Diagram Viewer



Single Line Diagram View: Pre-Fix, 340011_Chudleigh Knighton

Edit Edge

Name: L1334_2_N3222

Edge Type: Cable

Colour: Grey

Opacity: 100 %

Label:

Width: 4

Z Index: 0

Minimum Zoom: %

Maximum Zoom: 2147483647 %

Resistance: 0.0000256688272401 Ω

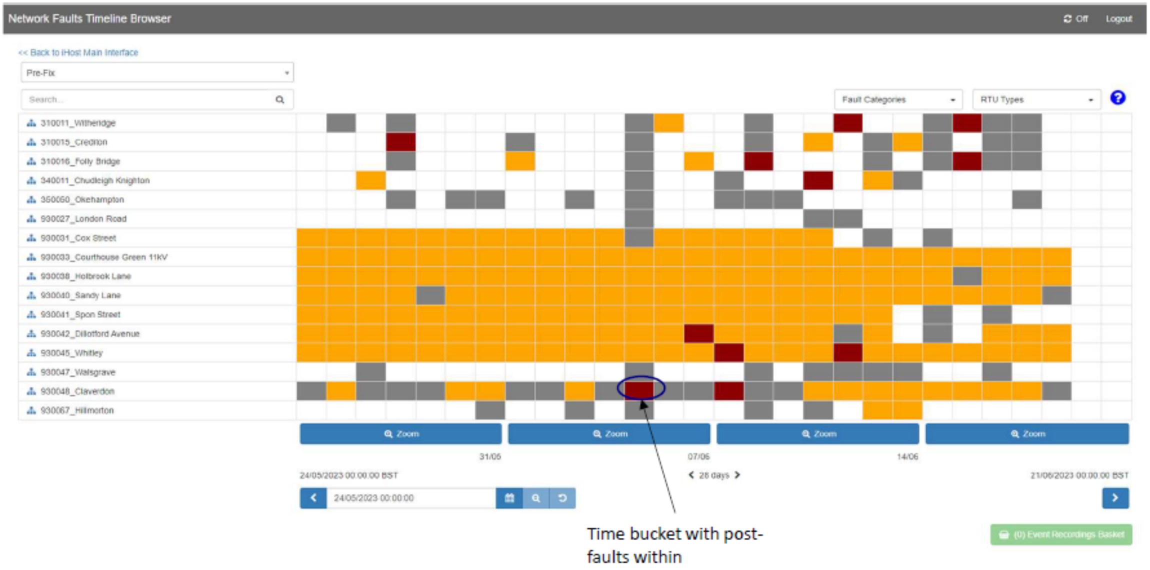
Reactance: 0.0000348171857009 Ω

Figure 8 - Single Line Diagram Interactive Editor

2.4.1.4. Network Faults Timeline Browser

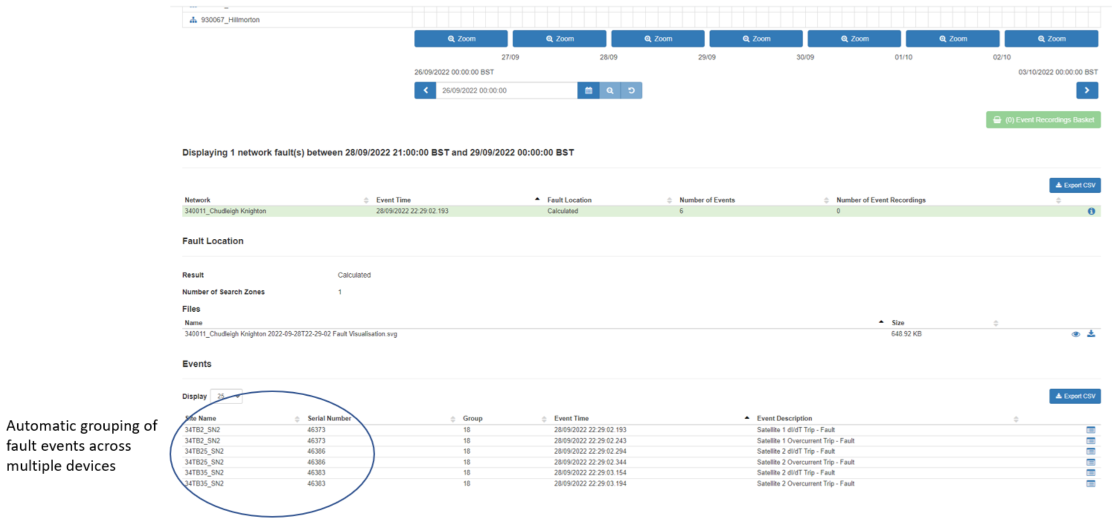
The Network Faults Timeline Browser feature within C-DIP provides business users with an overview of device activity, grouping by substation and pre-defined time windows as well as pre- and post-fault activity. The feature provides a drilldown so that groups of events can be analysed with greater granularity as and when required. The timeline browser dashboard allows a drill-down to view event grouping initially over a 28 day period with 1 day grouping, then a 7 day period with 3 hour grouping, then a 1 day period with 30 minute grouping. The matrix also provides the distinction between pre-fault and post-fault events allowing the user to filter the matrix depending on their analysis priorities.

The Network Faults Timeline Browser interface is given in Figure 9a and 9b respectively.



Time bucket with post-faults within

Figure 9a - Network Faults Timeline Browser



Displaying 1 network fault(s) between 28/09/2022 21:00:00 BST and 29/09/2022 00:00:00 BST

Network	Event Time	Fault Location	Number of Events	Number of Event Recordings
340011_Chudleigh Knighton	28/09/2022 22:29:02.193	Calculated	6	0

Fault Location

Result: Calculated

Number of Search Zones: 1

Files

Name	Size
340011_Chudleigh Knighton 2022-09-28T22-29-02 Fault Visualisation.svg	648.92 KB

Events

Site Name	Serial Number	Group	Event Time	Event Description
34TB2_SN2	46373	18	28/09/2022 22:29:02.193	Satellite 1 dI/dT Trip - Fault
34TB2_SN2	46373	18	28/09/2022 22:29:02.243	Satellite 1 Overcurrent Trip - Fault
34TB25_SN2	46386	18	28/09/2022 22:29:02.294	Satellite 2 dI/dT Trip - Fault
34TB25_SN2	46386	18	28/09/2022 22:29:02.344	Satellite 2 Overcurrent Trip - Fault
34TB35_SN2	46383	18	28/09/2022 22:29:03.154	Satellite 2 dI/dT Trip - Fault
34TB35_SN2	46383	18	28/09/2022 22:29:03.194	Satellite 2 Overcurrent Trip - Fault

Automatic grouping of fault events across multiple devices

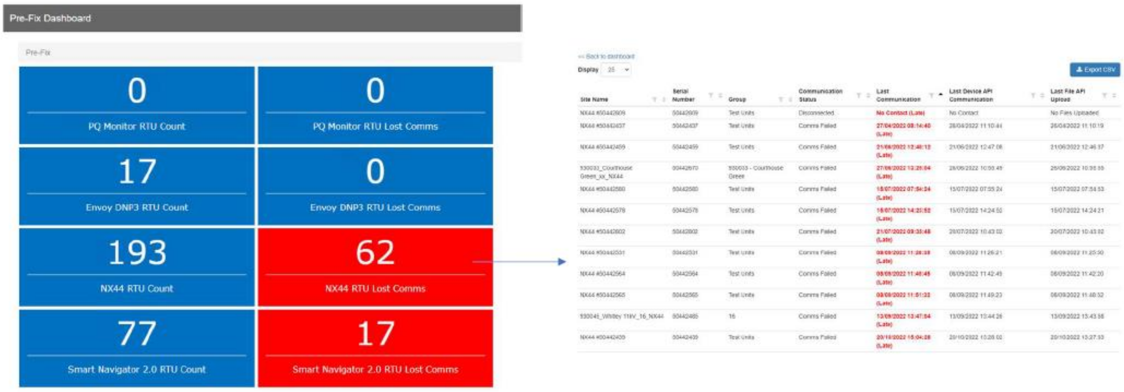
Figure 9b - Network Faults Timeline Browser – Activity Drill-down

Each cell represents a time bucket for events associated with a particular primary substation. White cells indicate no activity, amber cells indicate pre-fault activity, dark red cells represent post-fault activity and grey cells represent indeterminate activity. By clicking on a bucket of activity, the user is able to view all the devices and disturbances that underpinned the event, automatically grouped together. The user can also access waveform viewing features as described in the preceding sections. The interface is interactive and the user can navigate backwards and forwards in time to determine what, if any, pre-fault activity took place before a post-fault event. The time-geography representation of events also allows the business user to determine if a network-wide event has occurred, simultaneously affecting multiple primaries and/or HV feeders.

Feeders with high pre-fault activity are being screened to filter out noise and load pickups, allowing for easier analysis of distinct events. This is done using a Fourier series analysis of the waveforms uploaded to iHost by devices in the field and a rule-based algorithm that considers signal to noise ratio and waveform RMS during the capture time period.

2.4.1.5. Device Health Dashboard

The Device Health Dashboard feature is illustrated in Figure 10. This gives business users insight into the communications health of the fleet of devices contributing to the automated analysis and decision-informing within C-DIP.


Pre-Fix Dashboard

Pre-Fix

0 PQ Monitor RTU Count	0 PQ Monitor RTU Lost Comms
17 Envoy DNP3 RTU Count	0 Envoy DNP3 RTU Lost Comms
193 NX44 RTU Count	62 NX44 RTU Lost Comms
77 Smart Navigator 2.0 RTU Count	17 Smart Navigator 2.0 RTU Lost Comms

Figure 10 - Device Health Dashboard

2.4.1.6. Fault Location (FPI Search Zone)

The fault location feature of C-DIP, based on automatically generated FPI search zones, is given in Figure 11. The amber line traces the flow of the fault from primary to fault location. The red zone represents the most likely fault location based on the real-time status of FPI post-fault alarms. In the pre-fault domain, the amber traces the current flow to defect and the red zone represents the most likely defect location.

This is a powerful feature as it embeds expert knowledge within C-DIP to give business users insight into the geographical location of pre- or post-faults within minutes of the network disturbance event occurrence.

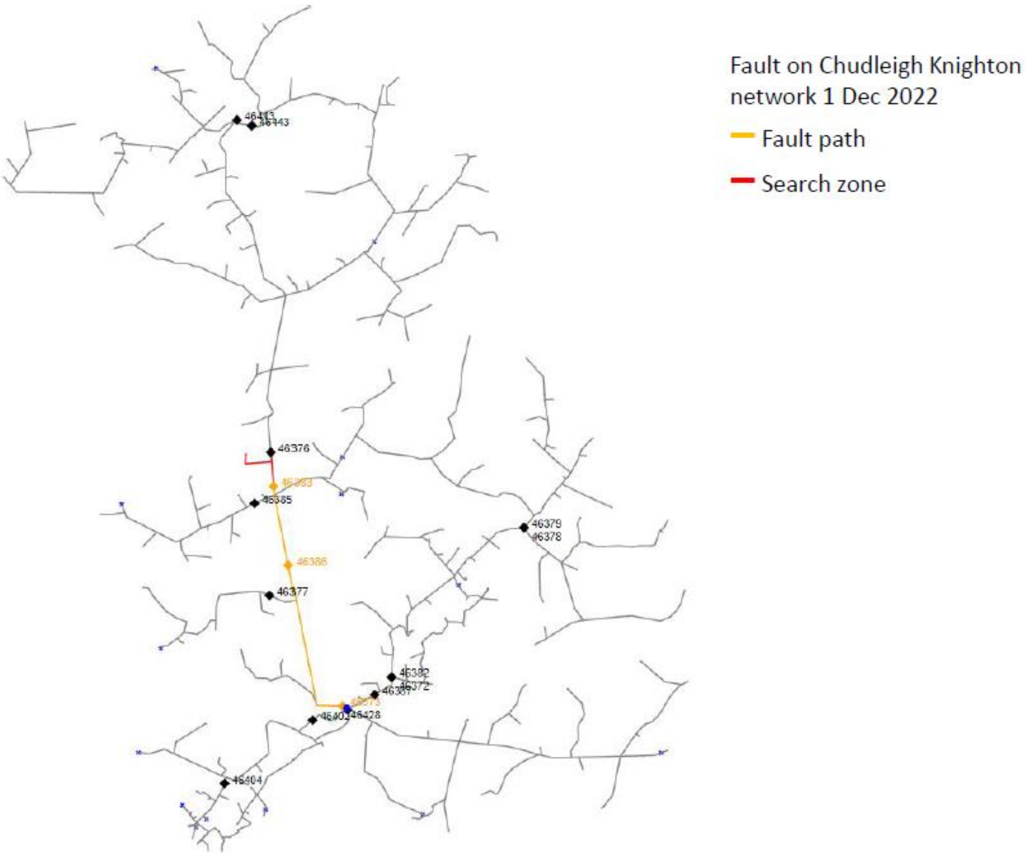
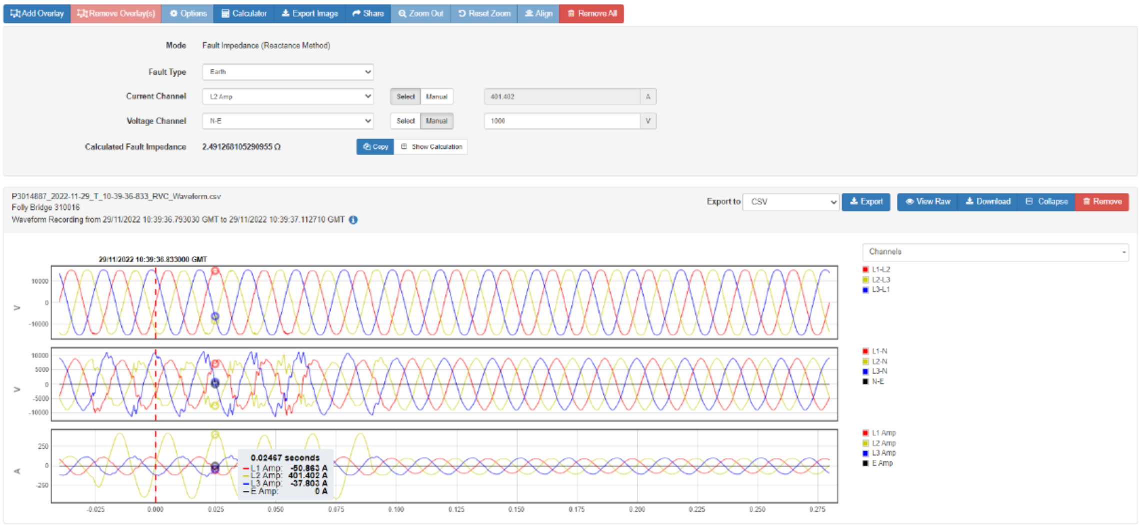


Figure 11 - Illustrative FPI search zone (reducing network search zone by 80%)

2.4.1.7. Fault Location (impedance-based pre and post-fault distance assessments)

The Fault Location feature of C-DIP, using impedance-based pre- and post-fault distance assessments, is given in Figure 12. The system (or, in manual mode, the user) automatically selects the point-on-wave to analyse the network disturbance and determine impedance-to-fault based on the number of parallel transformers in operation at the time of the disturbance.

This is an incredibly powerful feature as it embeds expert power systems analysis within C-DIP to give business users insight into the fault type and impedance-to-fault for pre- or post-faults within minutes of the network disturbance event occurrence. This process is currently manually completed by the user for control over the point-on-wave selection and other input parameters. However, the expectation is that this process will be fully automated within the system, with benefits demonstrated, prior to the end of the project.



Mode: Fault Impedance (Reactance Method)

Fault Type: Earth

Current Channel: L2 Amp — Select — 401.402 A

Voltage Channel: N-E — Manual — 1000 V

Calculated Fault Impedance: 2.491268105290955 Ω

P3014887_2022-11-29_T_10-39-36-833_RVC_Waveform.csv

Folly Bridge 310016

Waveform Recording from 29/11/2022 10:39:36.793030 GMT to 29/11/2022 10:39:37.112710 GMT

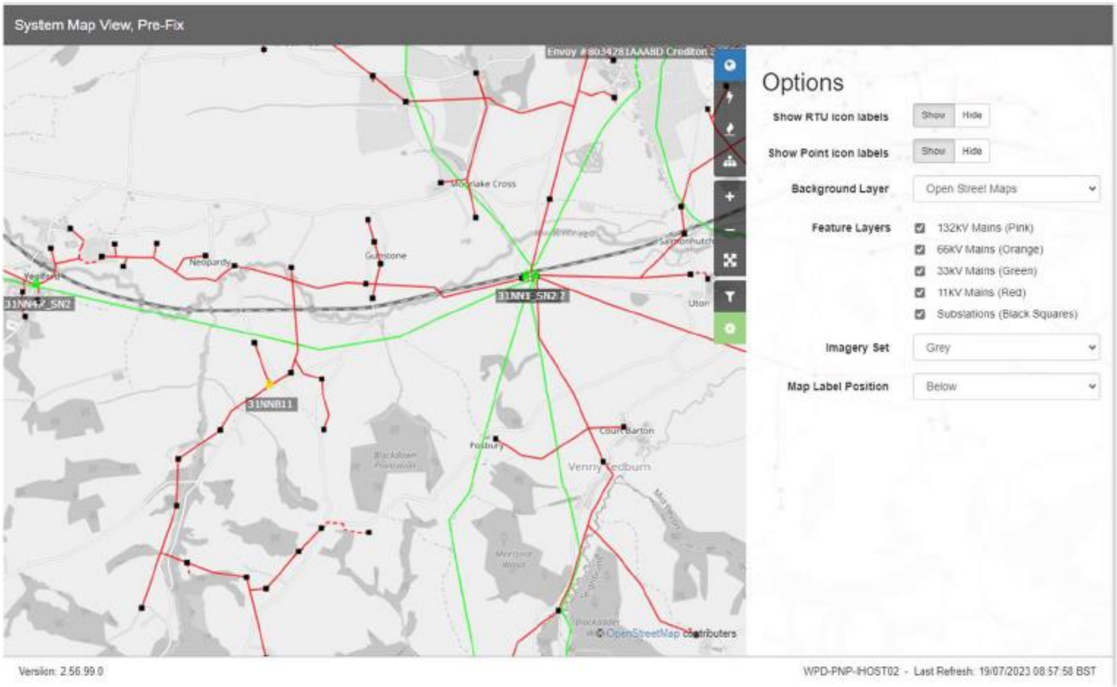
Export to: CSV

0.02467 seconds
L1 Amp: -50.863 A
L2 Amp: 401.402 A
L3 Amp: -37.803 A
E Amp: 0 A

Figure 12 - Impedance to Fault Calculation Engine

2.4.1.8. Geo-Server Integration

In order to optimise business use of the system and pave the way for business-as-usual adoption, the geographical plotting of fault locations (underpinned by SINCAL model ingestion and conversion described in preceding sections) was integrated with NGED's GIS by way of GeoServer. As seen in Figure 13 and Figure 14, this gives the business users the facility to access real-time updates of disturbance locations and likely root causes. After calculating an impedance to fault in the event recordings viewer, the user can plot the value on the network model to obtain a fault location predication.


System Map View, Pre-Fix

Options

Show RTU icon labels: Show | Hide

Show Point icon labels: Show | Hide

Background Layer: Open Street Maps

Feature Layers:
- ☑ 132KV Mains (Pink)
- ☑ 66KV Mains (Orange)
- ☑ 33KV Mains (Green)
- ☑ 11KV Mains (Red)
- ☑ Substations (Black Squares)

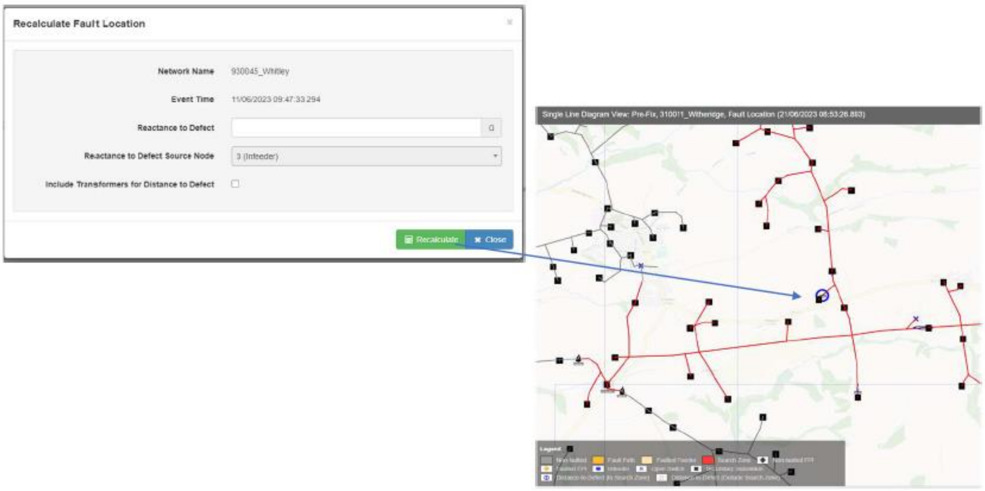
Imagery Set: Grey

Map Label Position: Below

Version: 2.56.99.0

WPD-PNP-IHOST02 - Last Refresh: 19/07/2023 08:57:58 BST

Figure 13 - GIS integrated within C-DIP


Recalculate Fault Location

Network Name: 930045_Whitley

Event Time: 11/06/2023 09:47:33.294

Reactance to Defect: Ω

Reactance to Defect Source Node: 3 (Infeeder)

Include Transformers for Distance to Defect: ☐

Single Line Diagram View: Pre-Fix, 310011_Witheridge, Fault Location (21/06/2023 08:53:26.893)

Figure 14 - Fault Location Geo-plotting

2.4.1.9. Automated Data Cuts

The development of the suite of C-DIP features was facilitated by an automated data cut feature that allowed live operational data to be extracted from the operational system (NGED's on-premises iHost) and automatically imported to the development system (Nortech's on-premises iHost) for feature development, testing and further refinement. This de-risked the software development process as it allowed development against live, real-life, data but decoupled from the live operational system. The use of iHost-to-iHost integration overcame systems integration challenges and allowed the transfer of data to take place in a secure and controlled way. The automated data cut process is shown in Figure 15.

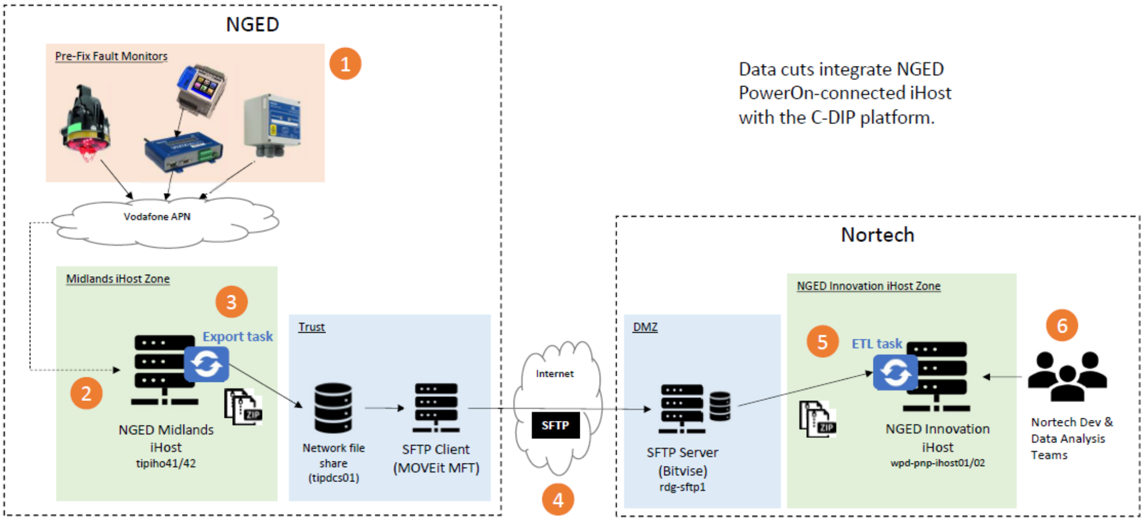


Figure 15 - Automated Data Cuts (iHost-to-iHost)

2.4.1.10. Real Time transmission of Waveforms

For the purposes of Pre-Fix, the suite of features within C-DIP is completed by the automatic transmission of waveform data on event creation by the source devices. Within 10-minutes of a disturbance event, the source data is automatically analysed to determine fault type and location as well as classification. This gives business users (in particular operational users) a much deeper insight into the geographical source of a network fault or disturbance and the most likely root cause. In the post-fault domain, this allows operational staff to make better-informed switching decisions to restore supplies to customers more effectively and efficiently. In the pre-fault domain, this information helps to inform proactive fault mitigation decisions (for example, overlay of cable to circumvent suspected faulty joint locations).

2.4.2. Device Installation

Since the last report, we have delivered the following device installation activities as summarised in **Error! Reference source not found.**.

	Total Installed
PQUBE	17
SN2	76
Clip-on NX44	112
Hard Wired NX44	34

Table 2 ***Device installation to date.***

We now have 17 PQMs installed and working across the East Midlands and South West licence areas. PQ monitors need to be retrofittable within existing 11kV panels within the Primary substation to monitor the 11kV data feed from 33/11kV transformers. The monitors trigger on network disturbances to record wave forms associated with fault and pre-fault activity. For the purposes of Pre-Fix, the voltage and current analogues from PQ monitors, and the events they record, are used to estimate impedance to defect (whether that be post-fault or pre-fault).

Smart FPI Installations in total the project team has installed 218 RTUs within the East Midlands and the South West licence areas. The device availability has increased since the new BETA firmware was released. At the beginning of March 2023 device availability was at 65%, a program of work to update the FPIs has been ongoing since Q1 2023 and has increased device availability to >95%. Some devices are still having issues but this is as a result of 4G network instability rather than the devices themselves.

To meet the scaling criteria, cable FPIs need to be retrofittable to existing 11kV Ring Main Units within Secondary Distribution substations and Feeder Breaker panels within Primary Substations to monitor the 11kV data feed from 11kV feeders. These devices need to detect and remotely communicate the passage of fault and pre-fault current through the network location where the FPI is installed. Cable FPIs need to trigger on network disturbances to record waveforms associated with fault and pre-fault activity.

OHL FPIs need to be retrofittable to existing 11kV overhead line circuits to monitor the 11kV data feed from 11kV feeders. It is preferable that these devices have the ability to be installed using an approved hot stick technique to avoid the need for a network outage. These devices need to detect, locally indicate and remotely communicate the passage of fault and pre-fault current through the network location where the FPI is installed. Where possible OHL FPIs need to trigger on network disturbances to record waveforms associated with fault and pre-fault activity.

2.4.3. Waveform Classification Module

The classification methodology was published in the 2023 International Conference on Electricity Distribution (CIRED) (Waveform Classification Methodology). The classification algorithm was set up on the basis of using a convolutional neural network (CNN) pre-trained using datasets created to introduce permutations in signal-to-noise ratio (representing departure from ideal signal quality conditions and reflecting, more accurately, the signals received from field devices) and variations in the faulted phase for a wide range of common fault signatures.

An initial set of 21 electric fault signatures was used to train the CNN fault classifier based on the IEEE Power Engineering Society Technical Report 73: “Electric Signatures of Power Equipment

Failures”. This comprised overhead line, cable, transformer, capacitor and surge arrestor components, each of which has more than one common mode of failure.

The CNN was created using the open-source TensorFlow Keras module with three layers of convolution, 64 filters and a kernel size of three. Pre-training the model allowed for a faster user experience when it came to classifying a particular waveform automatically.

A total dataset size of 2100 was used for the initial classification and this was expanded to 2200 in re-training (following the detection of new fault types).

The C-DIP waveform classification module was tested on the bench with simulated data and in the field with real-life data.

Examples of the classifier output were published in the 2023 International Conference on Electricity Distribution (CIRED) but, for example, the template signature for an incipient cable joint fault from the IEEE PES Technical Report 73 was used to classify an incipient cable joint fault within the Pre-Fix trial network with 87.7% confidence.

A key novel feature of the classifier within C-DIP is that the CNN classifier is capable of being retrained in order to add new fault/pre-fault categories as real-life fault data is captured during the course of Pre-Fix and different fault/pre-fault types are verified.

2.4.4. Third Party Device Integration

A fundamental premise of Pre-Fix was to design the C-DIP in such a way that third party devices could be integrated to stack value on top of existing equipment and its existing functionality.

PQube3 Power Quality Monitors, Smart Navigator 2.0 overhead line FPIs, NX44 cable FPIs and LV substation monitors have all been integrated into the C-DIP for use in pre-fault and post fault analysis. In addition to this, compatibility of C-DIP has been tested with three different types of HV technologies: (i) Siemens’ SIPROTEC relay; (ii) Schneider T300 Ring Main Unit; and (iii) Schneider’s ADVC3 autorecloser. Work is planned to ensure that these devices have configurable settings available to trigger on pre-fault defects, in addition to being compatible for post-fault waveforms.

Illustrative waveforms demonstrating the compatibility with third party devices are given in Figure 16 and Figure 17.

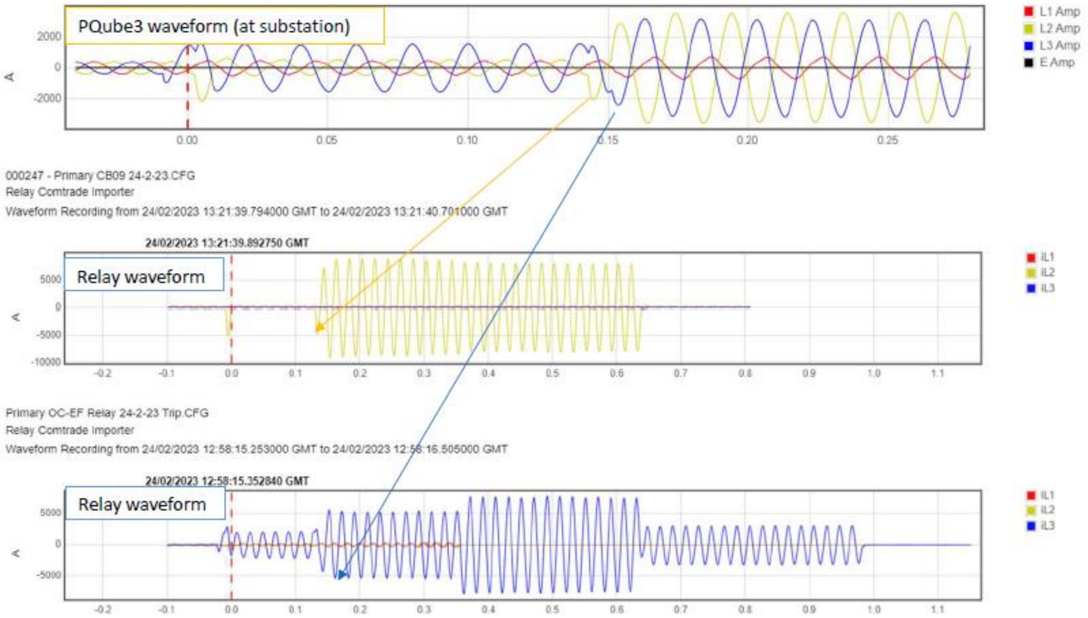
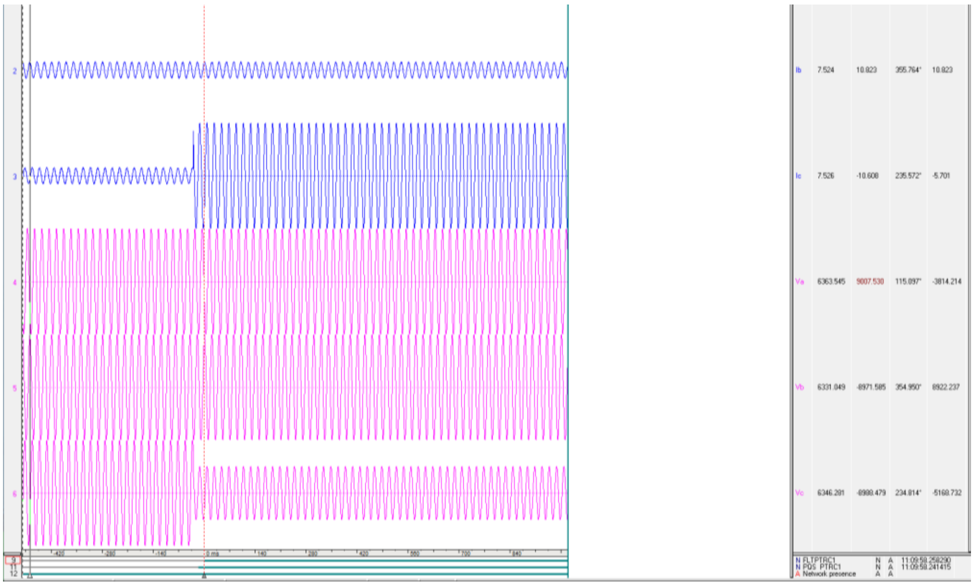
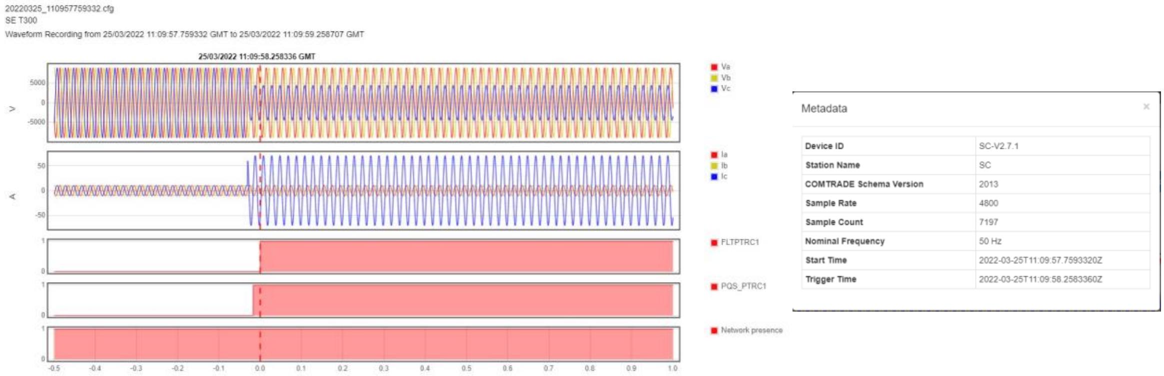


Figure 16 - Third Party Device Integration within C-DIP (Powerside PQube3 and Siemens SIPROTEC relay)



Ib	7.524	10.823	355.764°	10.823
Ic	7.526	-10.608	235.572°	-5.701
Va	6363.545	9007.530	115.097°	-3814.214
Vb	6331.049	-8971.585	354.950°	8922.237
Vc	6346.281	-8988.479	234.814°	-5160.732

N FLTPTRC1 N A 11:09:58.258290
N PDS PTRC1 N A 11:09:58.241415
A Network presence A A



20220325_110957759332.cfg
SE T300
Waveform Recording from 25/03/2022 11:09:57.759332 GMT to 25/03/2022 11:09:59.258707 GMT

Device ID	SC-V2.7.1
Station Name	SC
COMTRADE Schema Version	2013
Sample Rate	4800
Sample Count	7197
Nominal Frequency	50 Hz
Start Time	2022-03-25T11:09:57.7593320Z
Trigger Time	2022-03-25T11:09:58.2583360Z

Figure 17 - Third Party Device Integration within C-DIP (Schneider T300 RMU Automation)

The ability of relays to provide waveform disturbance data into C-DIP platform is shown in more detail within our CIRED 2023 abstract '*Delivering the benefits from a common disturbance information platform to prevent unplanned outages'*.

Relays need to fit into (or replace) existing 11kV panels within the Primary substation to monitor the 11kV data feed from 33/11kV transformers. The relays trigger on network disturbances to record wave forms associated with fault and pre-fault activity. Where the capability exists, relays need to generate and remotely communicate to PowerOn impedance to fault information. To date, we have shown how Comtrade files can be manually extracted from existing relays and uploaded onto the C-DIP. An equipment settings philosophy document has been developed to detail the requirements for cross manufacturer device triggering.

2.4.5. Pre-Fault Activity Reports

The project also sought to develop and validate standard reports that will enable consistent and effective pre-fault policy driven decision making to be made in an operational environment. Standardised reports for trial device activity have been implemented and regularly update users with a list of events that have occurred since the previous report. Summary reports for trial device activity between a selected date range have been developed which allow users to quickly identify all events within the date range and download the waveform data for each event in a chosen format.

2.5. Work package 5 - Trial

Trialling of the Pre-Fix solution since the last report, has seen success in both the pre-fault and post-fault domains.

2.5.1. Pre-Fault Analysis

The project has been reviewing trial data to determine what good pre-fault indicators of an impending fault are. We have also developed calculators for the I2t and impedance of an event. This allows the relative intensity of pecks to be compared across different sites and at the same location across different time horizons. These metrics are being quantified using real-world data from site trials and the results will form part of the learning outcomes of Pre-Fix.

The distance-to-defect approach adopted by the Pre-fix project team and implemented within C-DIP requires voltage and current values as input parameters to the algorithm. Using these parameters, the impedance-to-defect is quantified and the forward impedance path is extracted from the fault loop impedance. The forward impedance path is overlaid on the HV network to give HV feeder fault locations and to quantify distance-to-fault along the HV feeder(s) from the primary substation. Due to a lack of published research in this area, there is an underlying degree of uncertainty within the impedance loop and therefore there has been significant efforts to improve the accuracy of the impedance-to-defect calculation during the project. Further information on the learning gained in this area can be found in section 5.3.2.

Using Class I devices, the voltage during the network defect activity can be directly measured to feed into the distance-to-defect algorithm.

During Pre-fix, the team also pioneered an alternative, entirely novel, approach termed the ‘driving point voltage methodology’ that derived the voltage during network defects from the observed current of Class II devices (NX44s and smart Navigator 2.0s) and the known impedance to fault location. This voltage was then used to characterise the network to predict and localise pre-faults based on observed current measurements from other Class II devices but where the fault location was unknown as the feeder had not (and the time of the prediction) resulted in a post-fault condition. The driving point voltage was adjusted according to network characteristics (i.e. the cable/overhead line construction) and the nominal operating voltage of the HV network. The pre-fault predictions and network characterisation developed using this method means that pre-fault devices can be installed on networks with similar characteristics without the need for calibration.

Figure 18 - Pre-Fault Location Prediction Heat Map (later validated by post-fault coincident at hotspot location)

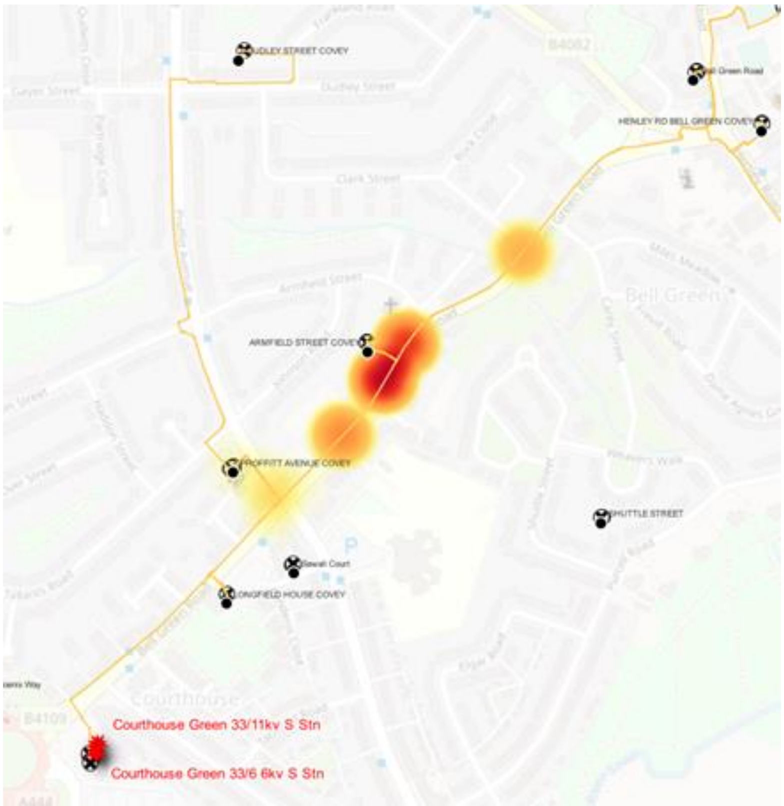


Figure 19 - Pre-Fault Location Prediction Heat Map

2.5.1.1. Validating Pre-fault Localisation Predictions using Post-Fault Locations

Error! Reference source not found. summarises the metrics in terms of pre-fault localisation validation using post-fault locational information for both underground cable and overhead line networks during the four-month trial period from 1st June 2023 to 30th September 2023.

Pre-fault location predictions were deemed to be acceptable if they were in the same circuit section as the post-fault location (i.e. within the same section when isolated by post-fault switching).

Table 3- Summary of Defect and Fault Locations for the period 1st June to 30th September 2023

	Pre-Fault	**Post-Fault (Ph-E)**	**Post-Fault (Ph-Ph)**	**Post-Fault (3-Ph)**
Underground Cable	7/7 (1)	6/6 (2)	4/4 (3)	3/3 (4)
Overhead line	4/4 (5)	- (6)	13/13 (7)	1/2 (8)
Total	**11/11**	**6/6**	**17/17**	**4/5**

(1) Based on genuine post-faults excluding manual maloperations and vandalism. Of 15 pre-fault observations, 8 were used to characterise the networks and the other 7 fault locations were predicted using the driving point voltage methodology and confirmed to be correct following a subsequent post-fault event.

(2) Post-fault locations for Ph-E faults were predicted based on pre-fault activity and locations were validated subsequently following post-fault events.

(3) Based on Ph-Ph post faults with known post-fault location.

(4) Locations were predicted by analysing the 3-Ph fault waveform at the zero crossing of one phase, using the Ph-Ph distance-to-fault algorithm and validating the prediction against the known fault location.

(5) Correct identification of an anomaly occurred at least 4 times, where the post-fault location could be validated. Additional predictions were made but are excluded from this results table as their exact location could not be validated (due to the common transient nature of faults on overhead line networks)

(6) The Pre-Fix project team are still deriving a methodology for predicting Ph-E fault locations on overhead line networks. During the trial to date, there have been 48 OHL phase to earth faults, 40 of which were transient and reclosed successfully. 8 of these faults were permanent but not ranged due to either loss of data recording or uncertainty with the impedance loop for phase to earth faults. Further learning on this topic is detailed in section 5.3.2.

(7) Locations were predicted using the Ph-Ph distance-to-fault algorithm and validated against known fault locations in the overhead line networks

(8) Locations were predicted by analysing the 3-Ph fault waveform at the zero crossing of one phase, using the Ph-Ph distance-to-fault algorithm and validating the prediction against the known fault location.

2.5.2. Post-Fault Analysis

Real world data has continued to be used since the last report, to determine fault locations post-fault. Post-fault location analysis combining FPI search zones and impedance based distance calculations has been successful in providing an accurate indication of fault location, which could be utilised to deploy field staff more efficiently. These predicted locations have been compared to actual fault/incident reports. We have successfully located 17 out of 17 Ph-Ph faults as shown in

Error! Reference source not found.. The D2F calculations, which were deemed to be acceptable if they were in the same circuit switching section as the post-fault location, successfully located all faults within the correct circuit section between 7m and 500m, as shown in Table 4. As discussed previously, the approach has been successful for phase to phase faults. Currently, the D2F calculations for phase to earth faults are not accurate enough and could not be used to deploy field staff more efficiently.

Table 4- Ph-Ph Location Accuracy Assessment

Date	Time	Network Type	Distance from Confirmed Fault Location
04/09/2023	20:46	Overhead line	130 metres
04/09/2023	14:51	Overhead line	300 metres
29/08/2023	15:25	Overhead line	500 metres
02/08/2023	08:52	Overhead line	100 metres
17/07/2023	07:42	Overhead line	280 metres
14/07/2023	05:07	Underground Cable	Within circuit section
12/07/2023	10:33	Overhead line	100 metres
27/05/2023	17:05	Overhead line	450 metres
09/05/2023	21:22	Underground Cable	300 metres
23/04/2023	15:57	Overhead line	7 metres
12/04/2023	17:56	Overhead line	24 metres
19/03/2023	21:47	Underground Cable	20 metres
10/03/2023	07:28	Underground Cable	300 metres
28/12/2022	14:18	Overhead line	160 metres
10/12/2022	09:38	Overhead line	240 metres
19/06/2022	19:58	Underground Cable	20 metres

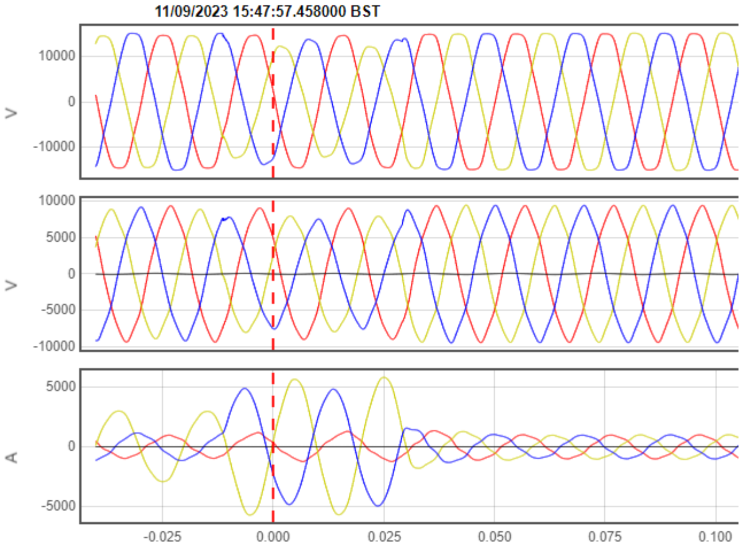


Figure 20 -Waveform captured during Ph-Ph fault and used for Distance-to-Fault Locating

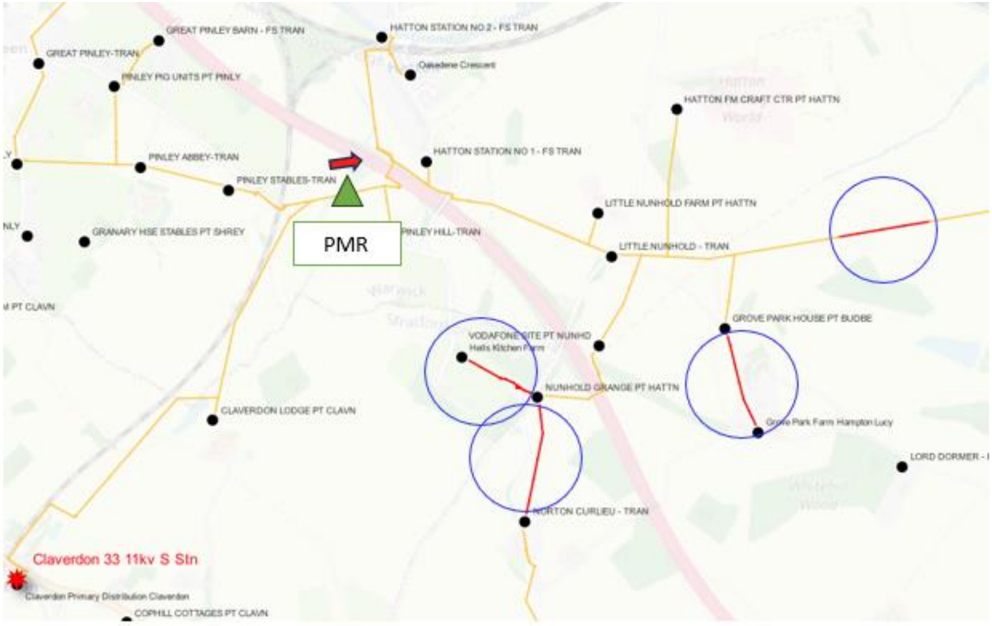


Figure 21 - Distance-to-Fault Locations yielding 4 search zones of ~100m each

The following sections provide further details of two case studies.

2.5.2.1. Crediton Feeder 18 Fault

At 17:56 on 12th April 2023, there was a fault on feeder 18 from Crediton primary. Both the FPIs (Smart Navigator 2.0s) and PQube detected the fault. A correct search zone was indicated by the FPIs and the PQube was used to determine an impedance to fault to indicate a fault location.

Figure 22 shows the fault current detected during the fault, which was determined to be downed conductors. Figure 23 shows the indicated FPI search zone, the DTF location and the actual location of the fault.

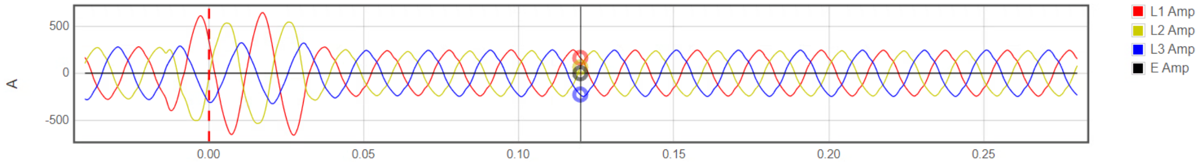


Figure 22 – Fault Current Observed from PQube_P3014852 during the Crediton fault on 12/04/2023

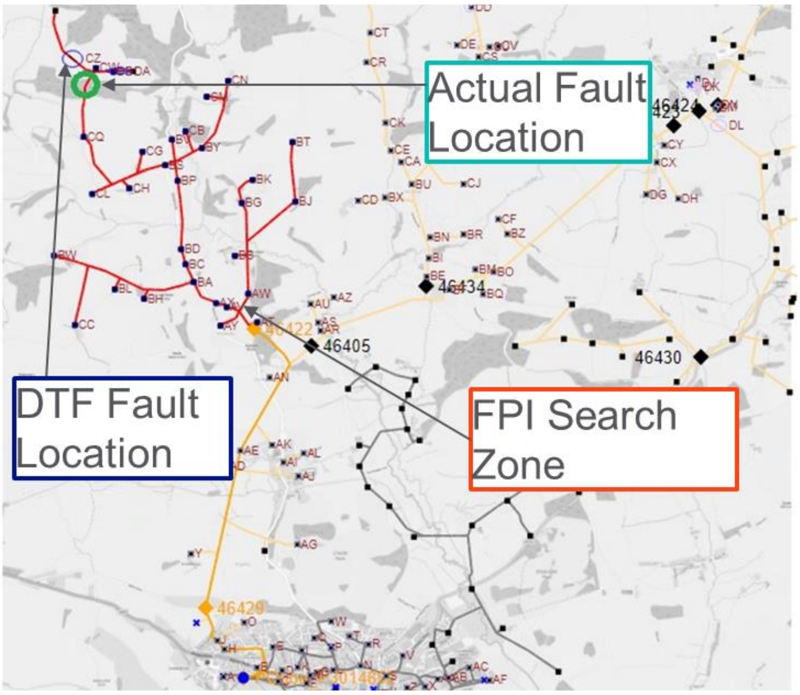


Figure 23 DTF Fault Location and Actual Fault Location for fault on Crediton Feeder 18 on 12/04/2023

In this case the Distance to Fault calculation was able to locate the fault within 24m of the actual fault location. This would have facilitated line patrols responding to the fault to be sent to actual fault location immediately, significantly reducing fault response times and associated CMLs.

2.5.2.2. Okehampton Feeder 22 Fault

At 14:51 on the 4th September 2023, there was a fault on feeder 22 from Okehampton primary. Both the FPIs and PQube device detected the fault. A correct search zone was indicated by the FPIs and the PQube was used to determine an impedance to fault to indicate fault locations. Figure 24 shows the fault current detected during the fault, which was determined to be downed conductors. Figure 25 shows the indicated FPI search zone, the DTF location and the actual location of the fault.

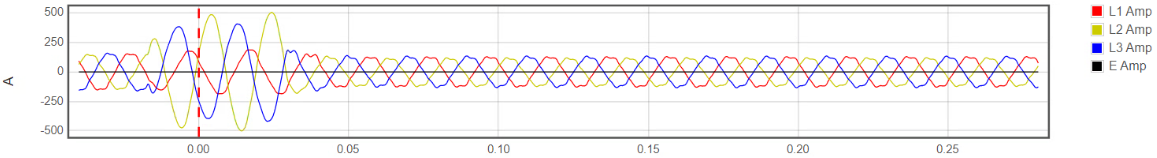


Figure 24 – Fault Current Observed from PQube_P3014885 during the Okehampton fault on 04/09/2023

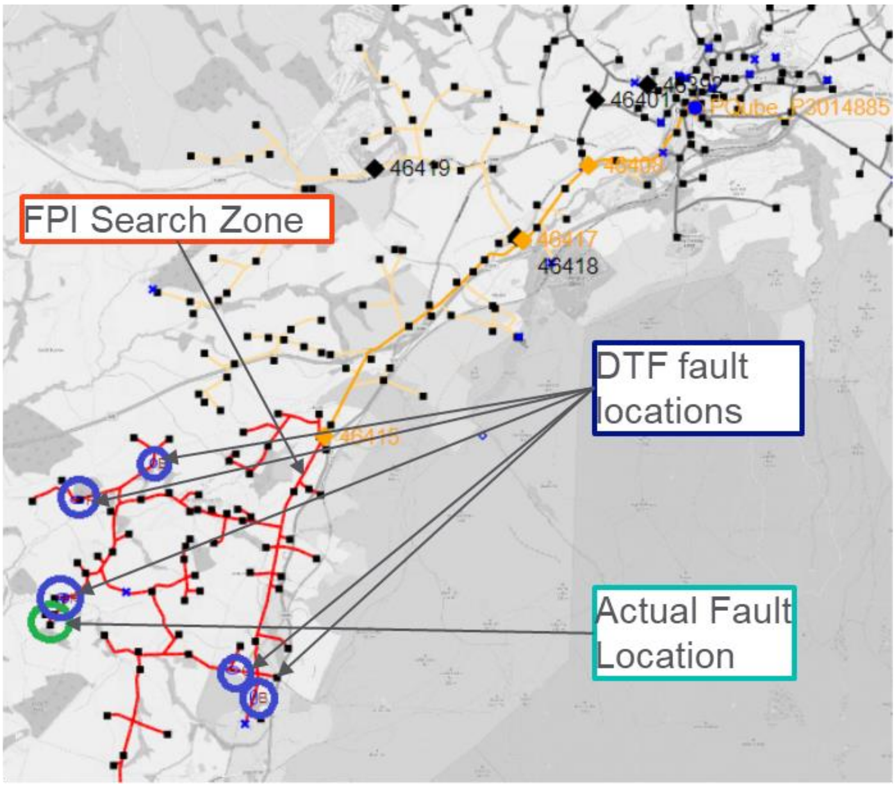


Figure 25 - DTF Fault Location and Actual Fault Location for fault on Okehampton Feeder 22 on 04/09/2023

Although the distance to fault calculation provides several fault locations, one of the locations was within 300m of the actual fault location. The correct identification of the FPI search zone would have facilitated engineers to isolate the fault more efficiently and DTF fault locations would have significantly reduced the time taken to locate the fault.

3. Progress against Budget

*Table 5**: Progress against Budget***

Spend Area	Budget(£)	Expected Spend to Date (£k)	Actual Spend to Date (£k)	Variance to expected (£k)	Variance to expected %
Project management and Technical Development	£240,916	£210,827	£197,269	£13,558	-6.43%
Network Services	£151,815	£151,815	£121,631	£30,184	-19.88%
Contractor Costs	£1,127,749	£1,082,402	£1,025,350	£57,052	-5.27%
Supply Chain Devices	£68,133	£68,133	£31,118	£37,015	-54.32%
Total	£1,588,613	£1,513,177	£1,375,368	£137,809	-9.1%

The project at this stage has a slight underspend due to the approved project extension until March 2024 and re-baselining of the budget. The project is on track to remain within budget, allowing for more data analysis and testing during the trial period. No contingency has been spent.

4. Progress towards Success Criteria

Table 6: Progress towards success criteria

Success Criteria	**Progress**
Demonstration of how to gather and then utilise data from existing NGED specification equipment in the pre-fault data chain, including protection relays and power quality monitors.	Complete: - A standardised set of reports have been designed to communicate pre-fault activity on feeders. - Summary reports for trial device activity between a selected date range have been developed which allow users to quickly identify all events within the date range and download the waveform data for each event in a chosen format.
Demonstration of how to gather then utilise data from temporary pre-fault monitors.	Complete: - Smart FPIs have successfully been retrofitted into feeder breaker panels with pre-fault ready settings. - Data from trail devices have been integrated with datasets such as network impedance models in order to provide operational outputs such as distance-to-defect.
Demonstration of how pre-fault information from diverse devices can be gathered into a central location.	Complete: - Data from trail devices have been integrated with datasets such as network impedance models in order to provide operational outputs such as distance-to-defect. - A paper has been published as part of the CIRED conferences showing the process for integration of data from other sources like CROWN and PowerOn. - Suppliers are being presented with a settings philosophy that includes minimum requirements and are invited to provide feedback on integration.
An application guide for how, where and when to deploy different pre-fault equipment.	In Progress: - End of project learning will be used to develop guidance on how to apply pre-fix output. - Escalation fits of smart FPIs are being organised in order to demonstrate how pre-fault activity seen by devices on the network can have locations confirmed and

	provide some insight into the process surrounding these actions. - Pre-Fault capable LV monitoring is being looked into too, as this will allow confirmation as to whether LV pre-faults are being picked up on the devices installed on the HV network
A user interface to present pre-fault data in a manner that is useful and meaningful to operational users.	In Progress: - We have designed and developed a user interface. - The currently implemented dashboard (event timeline browser) has events captured by trial devices classified as Pre-Fault/Post-Fault based on binary triggers from smart FPIs and presented in a time-block graph showing event types over time. - The event timeline browser groups events that have occurred within a given time frame on devices installed along the same primary substation/feeder in order to provide a user-friendly experience when looking to analyse an event. - The event timeline browser also allows users to locate system-wide disturbances as well as local feeder/primary grouped devices.
An prototype operational protocol for how to leverage technical application into operational outcomes	In Progress: - Operational protocols and method statement are currently under our development and review processes. - Trial escalation fits to confirm pre-fault locations (provided by distance-to-prefault algorithm) could provide the outcomes needed to both prove functionality and have assisted in development of protocols for the handling of pre-faults identified by technical processes. - The methodology for validating pre-fault predictions has been defined and is being tested.

5. Learning Outcomes

5.1. Device installation, set up and settings

5.1.1. Enhancing the functionality of C-DIP to analyse NX44 waveforms and filter out noisy captures

The functionality of C-DIP was enhanced to analyse the harmonic content of waveform captures and thereby distinguish genuine pre-fault activity (such as cable pecks, tree branch brushes) from noisy signals (as a result on an underlying power quality issue or where signal-to-noise ratios were too low to distinguish sensor signal from noise). Using this filtering technique, a population of 10,000 waveform captures was reduced to 3,000 meaningful waveforms for further analysis. The waveforms were independently checked for validation and confirmation that the filtering algorithm was behaving as expected.

5.1.2. Enhancing the functionality of Class I devices (PQube3) to introduce electrical current distortion triggers

Prior to Pre-Fix, the Class I power quality monitoring device (the PQube3) was designed to capture network disturbances based on voltage distortion triggers (this was, and still is, appropriate for harmonic/power quality assessment applications such as those specified in Engineering Recommendation G5/5). As part of Pre-Fix, the functionality of the PQube3 disturbance detection trigger was adapted to trigger on current, rather than voltage. This is because latent or evolving network defects exhibit an observable current signal disturbance that is not necessarily present in the corresponding voltage waveform signal. Following development and deployment, the use of current-based distortion triggers within the PQube3 led to enduring device communications (as device lock-ups from excessive waveform capture volumes were avoided) and this led to consistently reliable waveform captures for electrical current disturbances.

5.1.3. Device Installation

In order to deliver a cost-effective solution, Class 1 power quality monitors (PQMs) were installed on the secondary side of one (of two or three) primary transformers. The magnitude of monitored fault infeed was then multiplied by the number of transformers running in parallel to represent the total fault infeed (for distance-to-defect calculations). This approach is appropriate and valid if the normal running arrangement of the primary substation is with the primary transformers running in parallel. However, if the transformers are not running in parallel, the fault infeeds need to be independently monitored (i.e. with the installation of two or more Class 1 devices). A key recommendation in the context of the installation of Class 1 devices is to power them from the 110V DC uninterruptible power supply of the primary substation. If AC power is utilised, there is the potential for the power supply to the Class 1 device to be interrupted temporarily during earth faults and, therefore, the opportunity to capture fault waveforms during this period is lost. Moreover, for distance-to-defect assessments in earth fault conditions, it is vital that all three voltage signals (corresponding to L1, L2 and L3 respectively) are monitored. (In some legacy installations, the L2 phase is grounded and so the voltage signal corresponding to an earth fault on L2 is not able to be monitored).

The device installation architecture of Pre-Fix also deploys Class 2 devices (NX44s for the purpose of capability demonstration) into feeder breaker panels at the head end of each HV (11kV or 6.6kV) feeder. This cost-effective approach allows the electrical current disturbances seen by the Class 1 device to be attributed to a particular feeder for circuit localisation and distance-to-defect assessments. This approach reduces the cost of installation to a point that is scalable across the network and removes any requirement to recommission circuit breakers. Direct triggering of the Class 1 (Pqube) from Class II devices (NX44s) will be tested in Q4 2023 along with the supply of the devices from an 110V DC supply to prevent the loss of data during phase to earth faults.

5.1.4. Selection of device pre-fault threshold settings

The selection of device pre-fault settings requires a trade-off and needs to be made such that devices are sensitive enough to capture pre-fault activity but not so sensitive that device memory storage becomes overloaded and/or so much data is captured that a significant burden is put of the data processing requirements of C-DIP.

In addition, a key learning outcome from Pre-Fix was to use signal distortion-based triggers for waveform captures, rather than simpler magnitude-duration threshold crossing settings. The use of distortion-based triggers inherently filters out changes in electrical current signals as a result of natural network activity (for example, motor start-up or load shift) and focuses on the disturbance of the underlying power transfer waveform as a result of defective network equipment (cables, transformers, overhead lines and the associated integrity of their insulation). We have also learnt that overcurrent triggers fill up the memory buffers but triggers based on current and voltage distortion rather than overcurrent allows more discriminatory noise rejection.

As part of Pre-Fix, a device settings philosophy document was produced to document recommendations and to specify required device functionality. This allows any third party vendors, looking to align their product with the goals of C-DIP, to understand the specific requirements and device performance required.

Recommended best practice is that COMTRADE files or other device waveform captures are transmitted in Combined COMTRADE file format (.cff) to avoid the header and data files being separated in transit and then not being able to be parsed within C-DIP for waveform visualisation and further analysis.

It has also been recommended that the use of overcurrent triggers be avoided due to avoid device memory being saturated. The device settings philosophy document outlines the preferred triggers for manufacturers to use.

Moreover, it is vital that each type of device (and the associated system architecture) is developed to support over-the-air firmware deployment and reconfiguration. This allows device settings to be adjusted without the need for time-intensive and cost-intensive site visits.

5.1.5. Surveying sites prior to device installation

Surveying sites prior to device installation is highly recommended to confirm that there is sufficient mobile coverage for device-to-C-DIP communications. Ensuring sufficient mobile coverage helps to improve/maintain the availability of devices contributing to C-DIP.

5.1.6. Robust capture of device metadata during the device installation process

A key recommendation resulting from Pre-Fix ix the development of commissioning tools that support the robust capture and record keeping of metadata associated with device installations. The whole distance-to-defect assessment process builds on the foundation of being able to trust that data from device ‘x’ is representative of the location in which device ‘x’ is installed on the network. Any errors in equipment location records or equipment serial number records propagate through the analysis system and lead to errors and uncertainties in system outputs (such as distance-to-defect assessments).

5.1.7. Matching the output of the secondary wiring to the device transducer rating

In order to optimise the device monitoring system (and limit as far as possible the noise in the signal-to-noise ratio), it is recommended that the primary-side rating of the transducer is matched to the secondary CT ratio of the circuit/component being monitored (e.g. a 2000/5 CT in the substation is monitored using a 5A rated transducer and a 2000/1 CT is monitored using a 1A rated transducer).

5.1.8. Feeder Breaker Voltage Signals

The use of busbar voltage signals combined with feeder breaker current can be used in distance-to-defect assessments to design out the requirement for voltage signals to be available and wired into each feeder breaker panel. This also offers a more cost-effective solution than installing a retrofit Class I device in each feeder breaker panel. The solution is achieved by a cross-trigger pilot wire that runs between Class 2 devices in the feeder breaker panel and Class 1 devices located on the transformer incomer(s). In this context, Class 2 devices need to have the functionality to send a binary output signal to Class 1 devices (with a binary state change on Class 2 device disturbance capture) and for the corresponding Class 1 device to have the capability of triggering a disturbance capture from a binary input signal received. Since Class 1 devices are installed (as previously noted) on one of several parallel infeeds, this also overcomes the limitation that the Class 1 devices only see ½ of the fault infeed contribution (or 1/x of the fault infeed, where x is the number of transformers running in parallel) and therefore they need to be configured to be more sensitive. This, in turn, can lead to challenges in the device discriminating between defects and natural network activity (such as load fluctuations) which ultimately results in unwanted and unnecessary additional waveform captures.

5.2. Detecting the Presence of Defects

This section of the report covers the following learning outcomes:

1. Waveform captures and what can be concluded from their analysis in terms of defect presence;
2. Waveform captures and what can be concluded from their analysis in terms of defect root cause;
3. Use of Class I device cross-triggering for enhanced information gathering.

5.2.1. Waveform Captures and the Presence of Defects

In order to correctly detect the presence of defects within HV networks, it was first necessary to minimise the noise associated with waveform captures. Noise filtering is an essential part of this process – this can be achieved partly by the capture devices themselves through the selection of appropriate disturbance trigger settings and the correct matching of transducer ratings to the rating of the equipment being measured (i.e. using a 5A rated transducer to monitor the secondary current of 2000/5 CT). However, key learning from Pre-Fix is that filtering within the data analysis function of C-DIP is also important as some noise is exhibited due to electrical network behaviour (for example, power quality issues). In Pre-Fix, the filtering of waveforms was achieved through AI algorithms that used Fourier Analysis to determine the harmonic content of waveforms as well as a time-series cycle-by-cycle comparison of waveforms during waveform captures. During a portion of the Pre-fix trial period (from June 2023 to August 2023), 10,000 waveforms were captured by field devices. Through the AI-filtering process, this was reduced to 3,000 meaningful waveforms that were analysed further to confirm the presence of defects, to classify the root cause and to provide insight into the defect location.

2023021400035421.cfg
930041_Spon Street_10_NX44
Waveform Recording from 14/02/2023 00:03:54.160000 GMT to 14/02/2023 00:03:54.260000 GMT

Figure 26 - Example waveform capture due to noisy input signal

2023041623490926.cfg
930041_Spon Street_10_NX44
Waveform Recording from 17/04/2023 00:49:09.210000 BST to 17/04/2023 00:49:09.310000 BST

-38.125 ms
I1: -36.13999999999987 A
I2: 35.7800000000002 A
I3: 20.90000000000009 A

Figure 27 - Example waveform capture due to presence of a genuine network defect

Based on the previously described waveform filtering analysis, a ‘watchlist’ of 68 HV feeders was generated that exhibited pre-fault activity in the 3.5 month period from 1st June 2023 to 16th September 2023. These feeders were then ranked according to the frequency and magnitude of defect activity as well as the energy[1] expended during the defect observed.

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[1] A metric of I^2t (used for defining electric fuse characteristics), was used as a proxy for energy

5.2.2. Waveform Captures and the Root Cause of Defects

Key learning regarding waveform captures and root cause analysis was captured and published in the 2023 International Conference on Electricity Distribution (CIRED), paper number 10747. This paper presented the application of machine learning, using a dynamic library of template electric failure signatures (built up from power quality waveforms), to detect component failures in HV distribution networks. For the first time, a solution has been created using equipment from multiple vendors to feed into the fault classification process, thereby overcoming the challenge of deploying resources to locate faults of unknown type. By the early identification of pre-fault power quality signal disturbances and understanding the likely component to fail, unplanned customer outages can be avoided by the DNO taking proactive mitigation steps and the reliability performance of the HV distribution network can be maintained or improved.

An initial set of 21 electric fault signatures was used to train the AI fault classifier based on the IEEE Power Engineering Society Technical Report 73: “Electric Signatures of Power Equipment Failures”. This comprised overhead line, cable, transformer, capacitor and surge arrestor components, each of which has more than one common mode of failure. Example waveforms for an incipient cable joint pre-fault and a cable joint fault is shown in Figure 28 and Figure 29. Outputs of the AI classifier give the user the closest match between the input fault signature data and a known fault signature type, along with a % certainty score.

In C-DIP, the user has the option to view the input data and the matched waveform as graphs, to allow for manual verification before continuing. Clearly, on occasions it could be possible for no match to be found (or to be found with a confidence outside of configured tolerances). In this case, these classifications are displayed as “no classification match”, to allow for these exceptions.

The IEEE report output was replicated in the UK HV context to verify its applicability. In particular, the cable joint incipient failure waveform was verified, through post-fault event analysis, to be a key leading indicator of cable joint failures.

A key novel feature of the classifier within C-DIP is that the CNN classifier is capable of being retrained in order to add new fault/pre-fault categories as real-life fault data is captured during the course of Pre-Fix. A total dataset size of 2100 was used for the initial classification and this was expanded to 2200 in re-training (following the detection of new fault types).

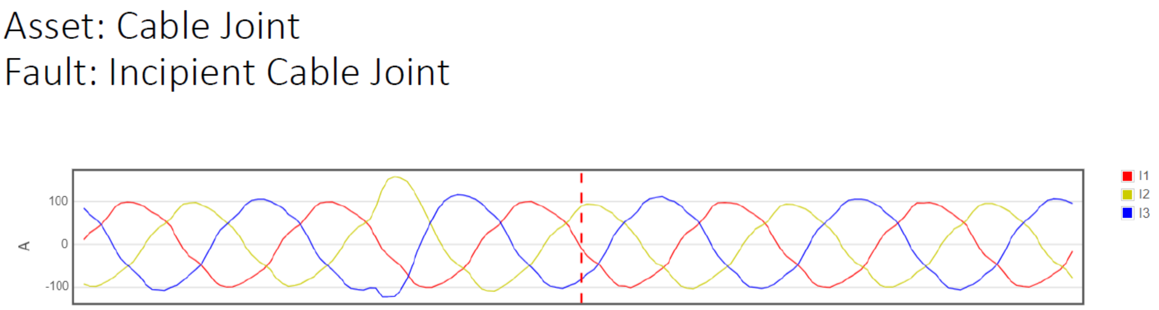

Figure 28 - C-DIP observed incipient cable joint pre-fault waveform (matched to IEEE report)

Asset: Cable Joint
Fault: Cable Joint Failure

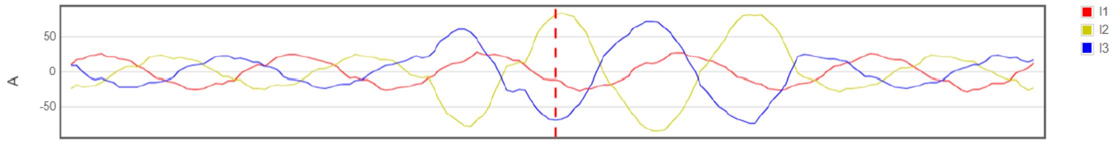

Figure 29 - C-DIP observed cable joint failure waveform (matched to IEEE report)

This also provides the index of waveforms that were captured by Pre-Fix and do not (yet) exist within the IEEE PES Technical Reports. Pre-fix has contributed to knowledge in this area and the new waveform captures have been used to expand the library of template signatures within C-DIP. One example of this, for a faulty OHL insulator, is shown in Figure 30.

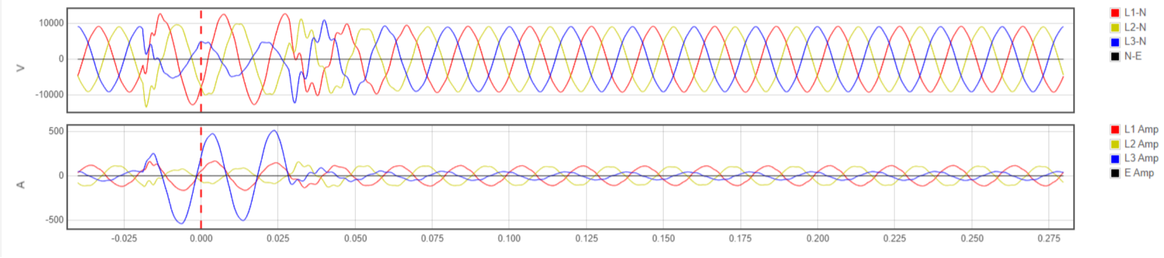

Figure 30 -C-DIP observed faulty insulator waveform (not contained in IEEE report)

Further validation of waveform classifications was achieved post-fault by confirming, after a defect had run to failure, that the pre-fault classification had selected the correct root-cause network component. For example, the classification of a cable pole termination defect allowed the search zone to be significantly reduced in a 15km overhead line feeder to just three locations (where overhead line terminated on poles for conversion to underground cable sections).

The waveform captures within Pre-Fix have also yielded waveforms that cannot yet be attributed to a particular root cause. For example, persistent three-phase current swells have been exhibited by more than one Primary substation in Coventry. Whilst this could be as a result of low voltage network disturbances, work is continuing in this area to investigate this phenomenon further. An example of this type of waveform is shown in Figure 31.

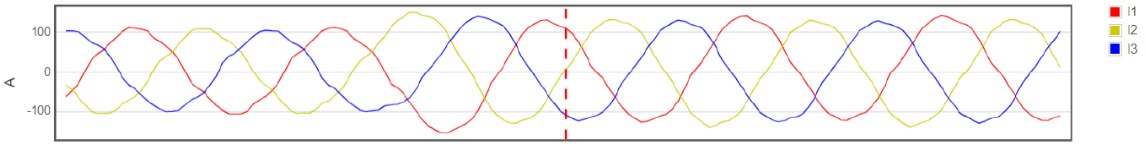

Figure 31 - Example of observed 3-phase swell

A key advantage of the C-DIP AI classifier is that further waveform archetypes can be added to the system as the body of knowledge expands. At present, the Pre-Fix project team is looking to instrument the HV network above LV networks with known pre-fault defects to understand how much, if any, of the LV pre-fault defect is observable at HV.

5.2.3. Cross-triggering Class I Devices based on Class II device disturbance triggers

Since Class I devices, such as Power Quality Monitors are installed on one of two (or more) transformer incomers, they only detect and observe half (or less) of the fault contribution. On this basis, particularly where the pre-fault level is close to maximum loading conditions, it can be difficult for the Class I device in isolation to discriminate between a disturbance event and nature network changes due to peak loading conditions. In order to maximise the benefits of high-resolution waveform captures (such as those delivered by Class I devices), a process of cross-triggering was explored whereby a Class II device at the head-end of the feeder (and thus observing the full fault contribution from upstream) was used to trigger a waveform capture of a Class 1 device. The method of achieving this has been discussed further in the previous section 5.1.8.

5.3. Localising Defects and Locating Post-Faults

This section of the report covers the following learning outcomes:

1. What we have learnt about the characteristics of pre-faults and their evolution into post-faults;
2. The use of post-fault location to validate pre-fault predictions and refine the methodology.

5.3.1. The Characteristics of Pre-Faults and Evolution into Post-Faults

Considering underground cable networks and the observation of HV defects, it is of note that the pre-fault waveform tends to exhibit a characteristic ‘phase-to-phase’ waveshape distortion but that the post-fault may, itself, be phase-to-phase or phase-to-earth. Figure 32 and Figure 33 show phase-phase pre-fault activity, with Figure 34 showing the post-fault phase-phase waveform. Similarly, Figure 35 and Figure 36 show phase to phase pre-fault activity, however Figure 37 shows that the resultant post phase fault is phase to earth in this instance.

Example of Ph-Ph pecks resulting in Ph-Ph post fault

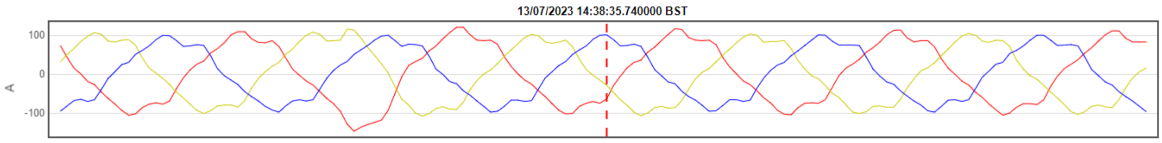

Figure 32 – Phase-Phase Pre-Fault Event for Phase-Phase Post Fault

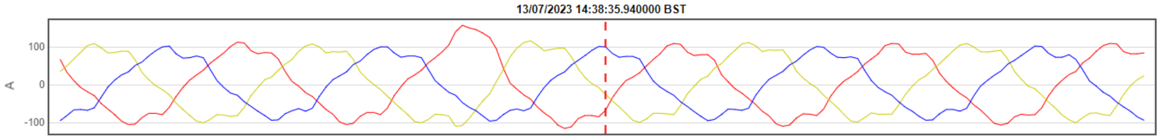

Figure 33 - Phase-Phase Pre-Fault Event for Phase-Phase Fault

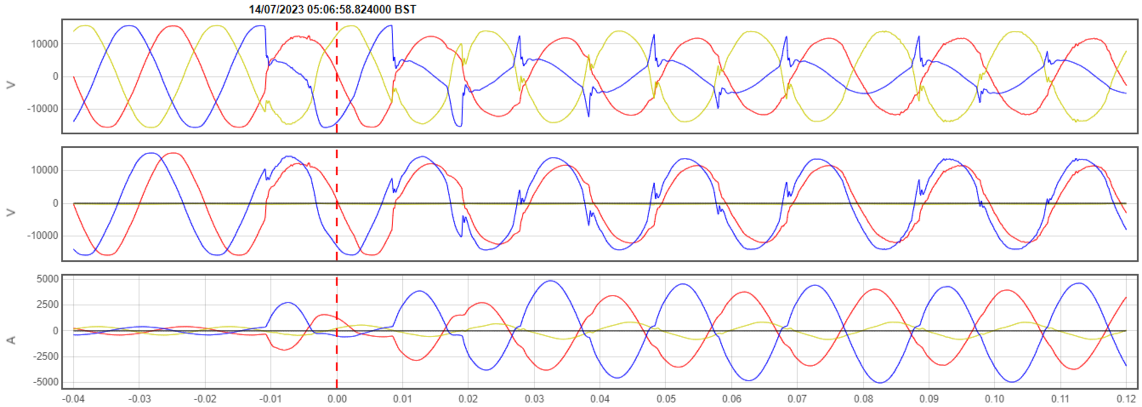

Figure 34 - Phase-Phase Post-Fault Event

Example of Ph-Ph pecks resulting in Ph-E post fault

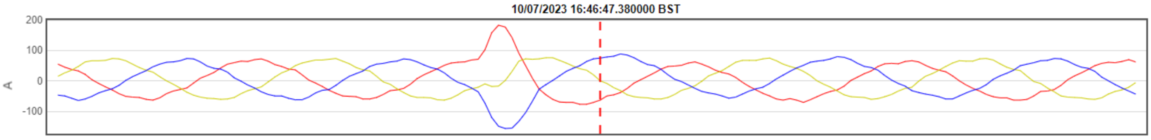

Figure 35 - Phase-Phase Pre-Fault Event for Phase-Earth Post Fault

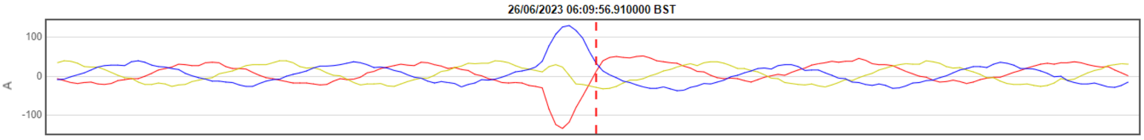

Figure 36 - Phase-Phase Pre-Fault Event for Phase-Earth Post Fault

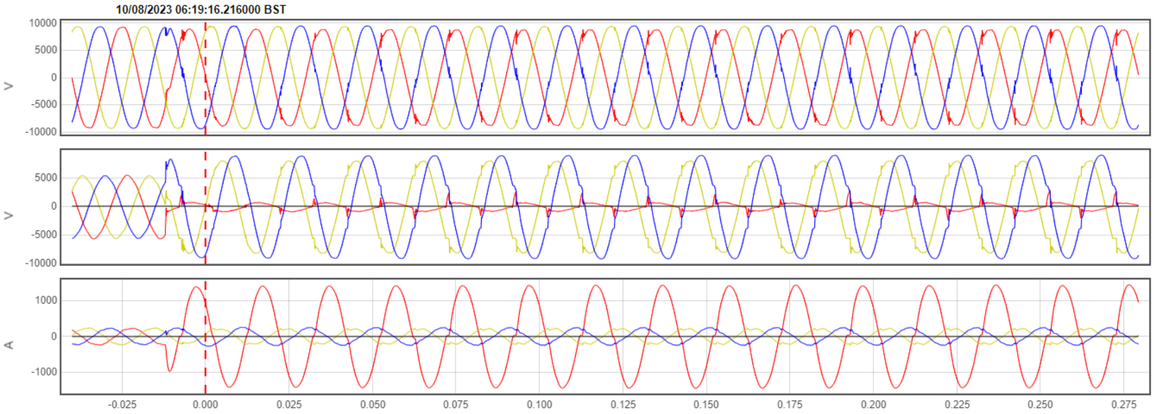

Figure 37 - Phase-Earth Post-Fault Event

5.3.2. Locating Post-Faults

For the purpose of post-fault location, electrical faults can be classified into balanced and unbalanced fault conditions. Balanced fault conditions include phase-to-phase and balanced three-phase faults. Unbalanced fault conditions include phase-to-earth, phase-to-phase-to-earth and three-phase-to-earth faults.

Whilst unbalanced three-phase-to-earth faults are the most complex faults to analyse and carry uncertainty in the quantifying the earth return impedance, this can be overcome by analysing the phase-to-earth or phase-to-phase portions of the waveforms during fault evolution.

The success of the results reported in Table 3 (Section 2.5.1) was attributed to the certainty with which phase-to-phase faults can be located. This is because the forward and return paths of the fault loop travel through the electrical conductors and their impedance is known with a high degree of certainty. Balanced three-phase faults can be analysed using the phase-to-phase methodology by selecting the point-on-wave where the third phase current travels through the zero-crossing and, thus, the contribution at that particular point in time can be assumed to be negligible. Furthermore, the pre-fault disturbance waveforms for cable networks, in particular, were observed to be phase-to-phase pecks and so the phase-to-phase analysis methodology could be applied with adjustments for the voltage in the pre-fault domain.

Considering the location of earth faults and developing the distance-to-fault methodology, detailed analysis was carried out on the fault loop impedance path of phase-to-earth faults on HV feeders of two different Primary substations within the Pre-Fix trial area. In both cases, the fault loop impedance path was found to be heavily dominated by the neutral (or liquid) earthing resistor with this impedance element alone representing 97% - 99.5% of the entire fault loop impedance. A recommendation has been taken forwards by NGED's business to assess NER/LER impedance characteristics more frequently to provide accurate up-to-date impedance data for fault location purposes. It is clear that a small error in assumed NER/LER impedance can lead to a significant difference in the overall impedance path (and ultimately leads to inaccuracies in the location of earth faults). Work is continuing in this area in the next phase of the Pre-Fix project.

5.4. Time-to-Fail Assessments and Observations

Key learning from Pre-Fix to date suggests that a significant spike in I^2t and the evolution of phases affected in pre-fault conditions (i.e. from one-to-two or two-to-three) are leading indicators of imminent failure. On six occasions during the four-month period from 1st June to 30th September 2023, the significant change in pre-fault characteristics was observed prior to the circuit failure (i.e. post-fault condition, interrupting supplies to customers).

The following case studies show examples of the change in pre-fault condition indicators prior to actual fault events and the time between the pre-fault event and eventual faults.

Case Study 1: Primary Substation in Coventry (Faulted: 18/08/2023 10:19)

In this case study all leading-indicator metrics plotted against time increased considerably 14 days prior to the post-fault event.

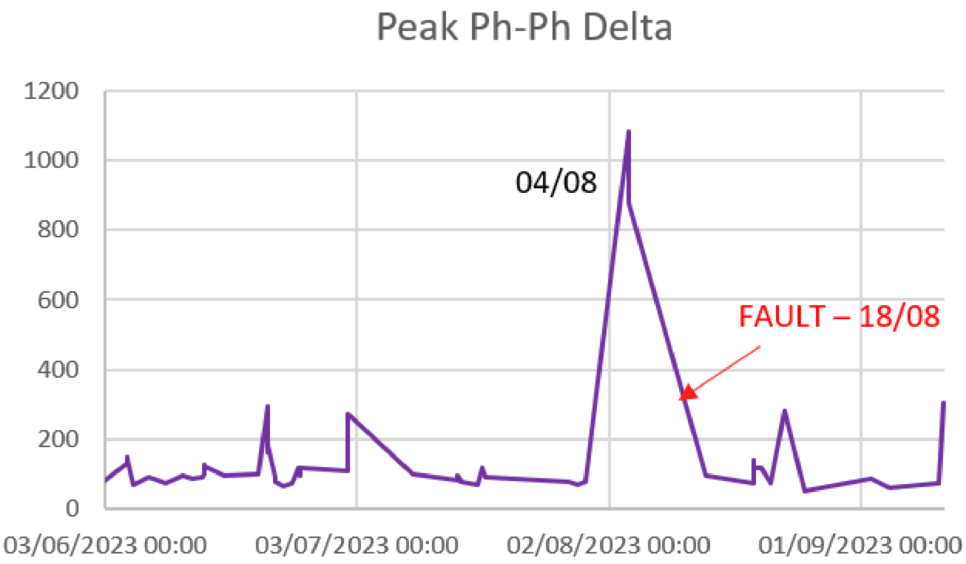

Figure 38 - A time-series plot of the delta change in ph-ph current (A) peaks during pre-fault activity leading up to a post-fault event

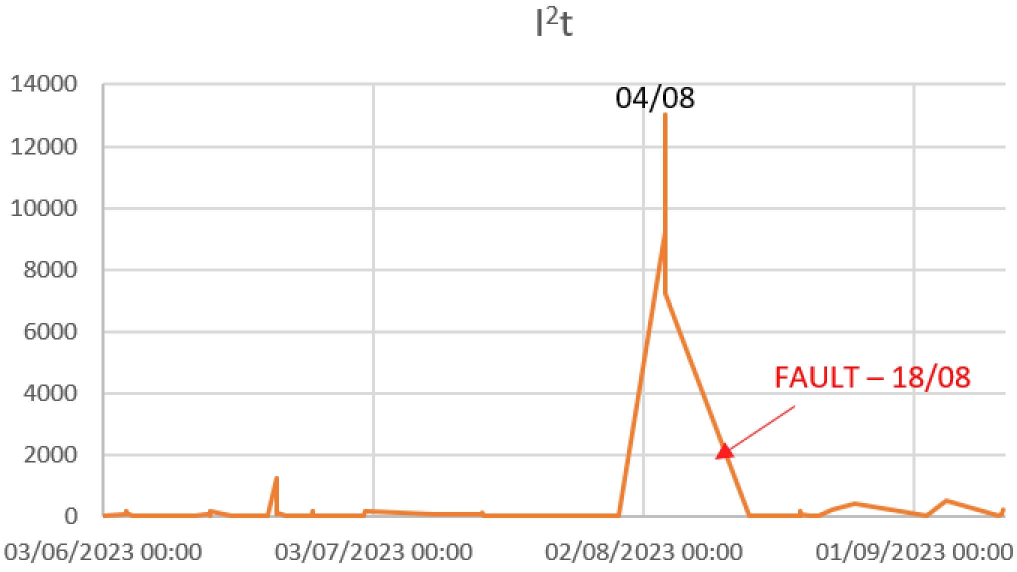

Figure 39 - A time-series plot of the change in I^2t (A^2s) peaks during pre-fault activity leading up to a post-fault event

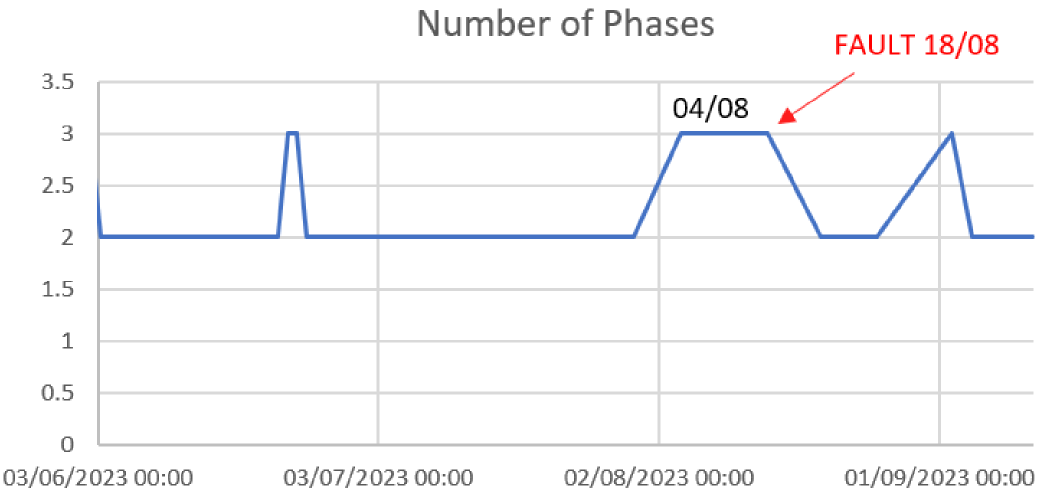

Figure 40 - A time-series plot of the change in phases affected by the defect during pre-fault activity leading up to a post-fault event

Case Study 2: Primary Substation in Coventry (Faulted: 06/06/2023 and 04/07/2023)

In this case study all leading-indicator metrics plotted against time increased considerably 9 days prior to the post-fault event.

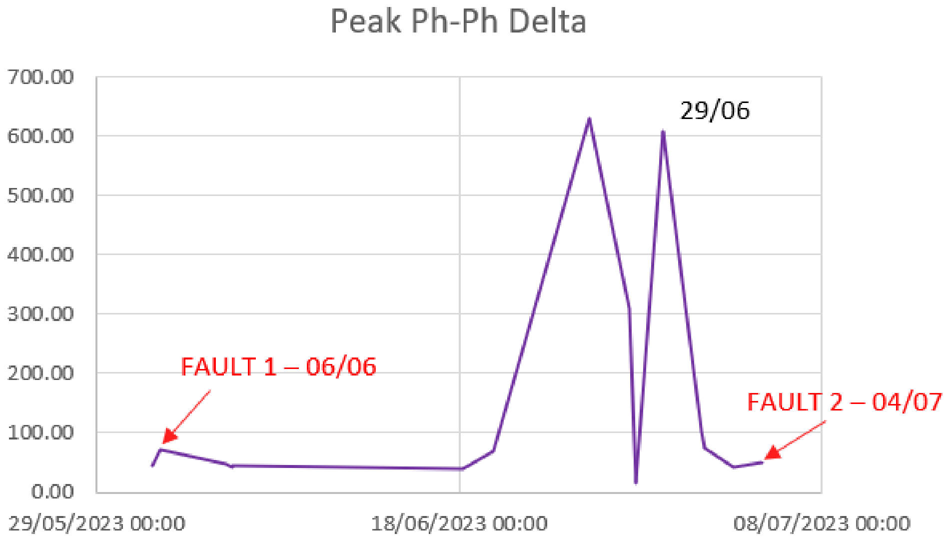

Figure 41 - A time-series plot of the delta change in ph-ph current (A) peaks during pre-fault activity leading up to a post-fault event

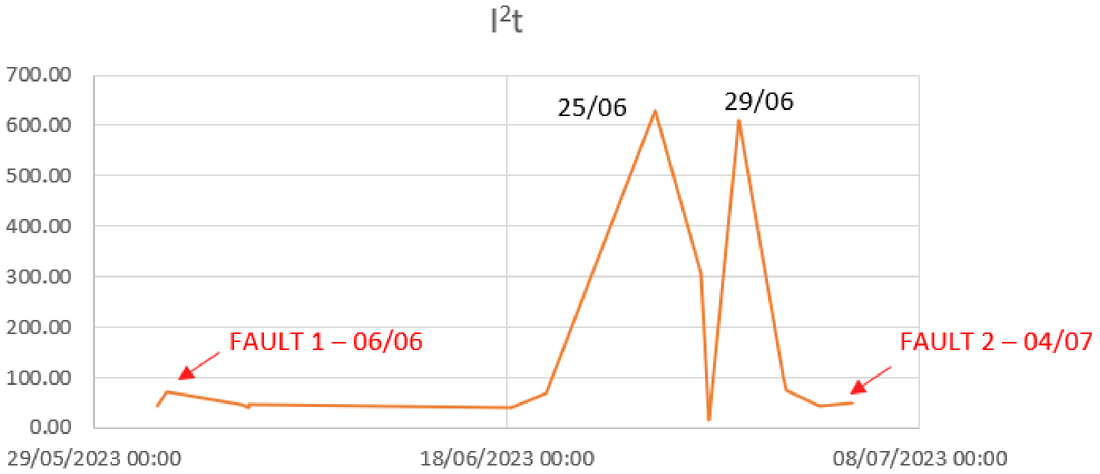

Figure 42 - A time-series plot of the change in I^2t (A^2s) peaks during pre-fault activity leading up to a post-fault event

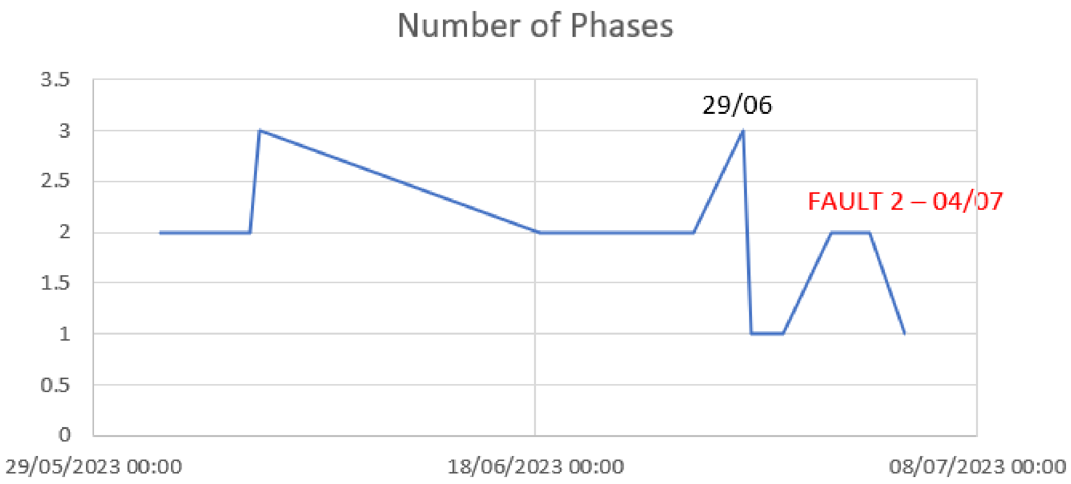

Figure 43 - A time-series plot of the change in phases affected by the defect during pre-fault activity leading up to a post-fault event

Error! Reference source not found. details six faults where a significant spike in I2t was witnessed before the fault. The time from the I2t spike to failure appears varied. Further analysis is planned for the remainder of the project to investigate the effect of various indicators on time to failure.

Table 7- Summary Table of Time-to-Fail Observations

Peak I^2t Event Date	I^2t peak magnitude (A^2s)	Fault Date	Fault Time	Time-to-Fail after I^2t spike
02/06/2023	2923	14/09/2023	18:05	3 months
29/06/2023	629	04/07/2023	19:05	6 days
10/07/2023	180	14/07/2023	05:07	4 days
04/08/2023	13,016	18/08/2023	10:19	14 days
05/08/2023	5,621	10/08/2023	10:59	5 days
21/08/2023	400	22/08/2023	22:51	1 day

6. Intellectual Property Rights

A complete list of all background IPR from all project partners has been compiled. The IPR register is reviewed on a quarterly basis. A complete list of all background and foreground IPR can be found on the Pre-Fix website.

7. Risk Management

7.1. Current Risks

The Pre-Fix risk register is a live document and is updated regularly. There are currently 29 live project related risks. Mitigation action plans are identified when raising a risk and the appropriate steps then taken to ensure risks do not become issues wherever possible. In this report we give details of our top five current risks. For each of these risks, a mitigation action plan has been identified and the progress of these are tracked and reported.

*Table 8- **Top five current risks (by rating)***

Details of the Risk	Rating	Mitigation Action plan	Progress
R032 – PQUBE3, NX44 or SN2 field failure	Moderate	1. Automate report 2. Nortech and NS response. 3.Hold spares 4. Dedicated NGED Resource to resolve device issues.	Availability of devices has been improved.
R038 - LV faults cannot be differentiated from HV faults	Moderate	Include extra analysis methods (e.g. AI training) to inform HV/LV fault differentiation	LV monitor data to be utilised to filter out LV fault waveforms.
R043 - Vendor devices have incompatible triggers	Moderate	Document required functionality Make use of device functionality in its current form	Device settings philosophy document has been completed
R035 - Vendor devices do not have acceptable disturbance trigger logic to enact the Pre-fix method	Moderate	Document required functionality Make use of device functionality in its current form"	Device settings philosophy document has been completed
R030 - Bugs in C-DIP/Inadequate performance	Moderate	Utilise data from other projects where not available in Pre-Fix	C-DIP performance improved through iterative design sprints.

7.2. Update for risks previously identified

Descriptions of the most significant risks, identified in the previous six monthly progress report are provided in **Error! Reference source not found.** with updates on their current risk status.

*Table 9- **Risks identified in the previous progress report***

Details of the Risk	Previous Rating	Mitigation Action plan	Progress
The current firmware of the PQUBE is not as sensitive as the NX44's and PQUBEs. This means that the PQUBE is blind to some PECKs	Major	Apply to Powerside for PQUBEs to incorporate the same current distortion trigger as the NX44 Alternatively, use an NX44 to trigger the PQUBE (Because it has a better trigger)	BETA firmware rolled out on all PQube3 with updated trigger thresholds. This risk is now closed.
The earth return path and arc impedance undermines the accuracy of the planned DTF method	Major	Calibrate the model on known faults. Review performance of reactive loop methodology. Explore alternative approaches.	Reduced to Moderate. Determined alternative methods for determining impedances where information within model is uncertain.
Failure of units in the field	Major	Weekly monitoring report to make sure devices are active and capturing Comtrade files	Reduced to Moderate risk, automated weekly reports, dedicated Nortech and NGED resource to respond to failures.
To link pre-fault observations to outcomes, we will need to witness circuits run to failure within project timescales	Major	Monitoring of device health to ensure device capture availability. Consider pro-active investigations towards the end of the trial if runs to failure have not been observed.	Risk reduced to Moderate. Weekly monitoring continues
High reliance on key Nortech Key individuals.	Minor	Raised with Nortech.	Risk closed, Nortech have expanded their delivery team to increase resilience

8. Consistency with Project Registration Document (PEA)

To ensure that we obtain the best return on research investment possible, project Prefix has been extended to run until the end of 2023/24. The updated PEA which reflects this change can be found here Pre-Fix PEA.

9. Accuracy assurance statement.

This report has been prepared by the Pre-Fix Project Managers (Greg Shirley and Samuel Jupe), reviewed and approved by the Innovation Manager (Paul Morris).

All efforts have been made to ensure that the information contained within this report is accurate. NGED confirms that this report has been produced, reviewed and approved following our quality assurance process for external documents and reports.

Glossary

Abbreviation	Term
BaU	Business as Usual
C-DIP	Common Disturbance Information Platform
SN2	Smart Navigator 2.0 – a self-powered overhead line monitoring device
NX44	A smart fault passage indicator that is mounted upon a ring main unit
NER	Neutral Earthing Resistor
LER	Liquid Earth Resistor
Ph-Ph	Phase to Phase
Ph-E	Phase to Earth
3-Ph	Three Phase
IPR	Intellectual Property Rights
CNN	Convolutional Neural Network
SLD	Single Line Diagram
OHL	Overhead Line
FPI	Fault Passage Indicator - A device for tracking abnormal current transients throughout the network
GIS	Geographic Information System
CT	Current Transformer
RMS	Root Mean Square
HV	High Voltage. Taken to be 11kV or 6.6kV within this report.
LV	Low Voltage. Taken to be 415V within this report.
Class I	Devices that can capture three phase current and voltage waveforms and broadcast the information in operationally useful timescales
Class II	Devices that can capture three phase current waveforms and broadcast the information in operationally useful timescales.

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